Robotic Lunar Surface Operations

Engineering Analysis for the Design, Emplacement, Checkout

and Performance of Robotic Lunar Surface Systems

Study performed for

NASA Ames Research Center

under Contract NAS 2 - 12108

Boeing Aerospace & Electronics

Huntsville AL

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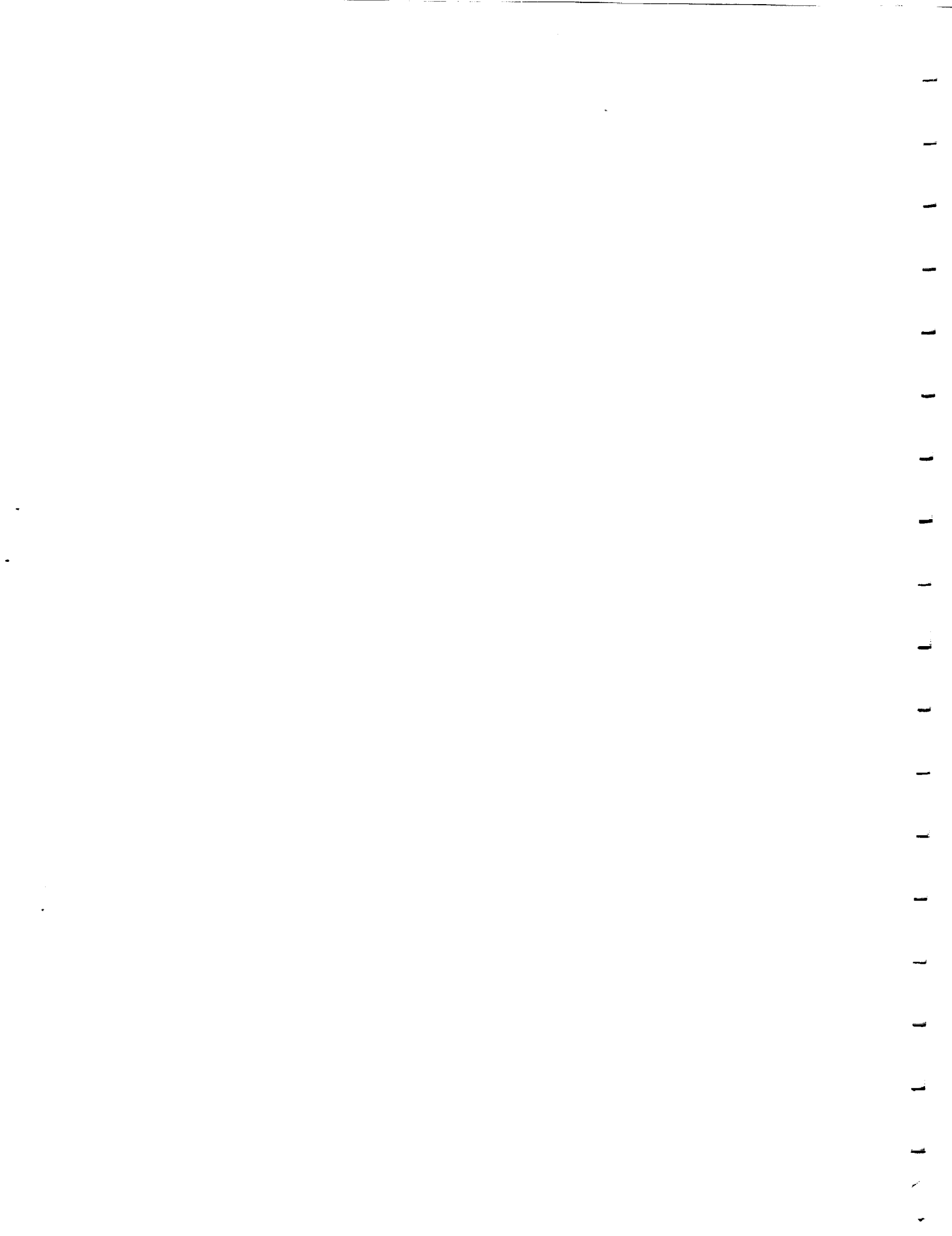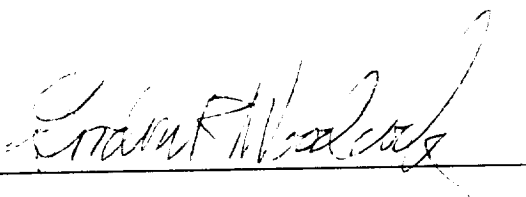
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Gordon R Woodcock
Study Manager

FOREWORD

This study was arranged to address the application of automation and robotics (A & R) to emplacing, activating and maintaining early planetary bases. NASA's Office of Exploration (OEXP, or Code Z) sought to broaden its assessment of the operational problems inherent in expanding human presence out into the solar system, and to stimulate informed thinking about possible solutions.

Two principal emplacement tasks on the Moon would be setting up and shielding a permanent surface habitation system, and beginning the extraction of oxygen propellant from lunar resources. Performing these tasks early, before onsite crew participation is prevalent, enhances crew safety and vehicle efficiency (for the former task), and overall program economy (for the latter). Furthermore, crew time on the Moon, and particularly extravehicular (EVA, or spacesuit) time, is extremely valuable; thus developing A & R techniques which can offload the base crew from routine maintenance tasks has high leverage for lunar base scenarios.

Conventional, first generation lunar base construction concepts tend to be grounded in familiarity with terrestrial construction sites. However, at all scales of implementation, the lunar case is so fundamentally different as to require fresh evaluation. The problems of alien geology; cumbersome mobile power; inadequacy of hydraulic mechanisms; hard vacuum combined with penetrating, abrasive fines; and impracticality of extensive onsite support all challenge simple solutions.

Robotics (in the sense of large, mobile, and dextrous machinery) was seen as strictly necessary for planetary base installation and operation. And automation appeared to offer great potential for overcoming the problems of controlling complex activities in hostile environments separated from Earth by interplanetary distances. A study was deemed necessary to analyze those problems, develop a reference base concept with sufficient and appropriate detail to permit then developing a specific A & R approach, and finally to evaluate the scenario's reliability, support requirements and implementation schedules.

The study was directed by Robert Mah of the NASA Ames Research Center (OEXP Special Assessment Agent for Automation, Robotics and Human Performance). Principal contractor contributors to the study were:

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GLOSSARY

Following is a list of definitions, as used in this study, for words easily capable of causing confusion in discussions of lunar bases and robotics.

TIME-PERIOD TERMINOLOGY

DAY, WEEK, MONTH, YEAR all have their common, Earth-based meaning.

CYCLE   The 28-day lunar diurnal cycle, consisting of one lunar day and one lunar night; shorter than most months; roughly 13 cycles/yr.

LUNAR DAY   The sunlit, daytime fortnight of a lunar cycle.

LUNAR NIGHT   The dark, nighttime fortnight of a lunar cycle.

INTERVAL   The period between lander arrivals (3 cycles in this case).

A & R TERMINOLOGY

AUTOMATION   The technique of giving over specified levels of task command to a machine.

CONTINGENCY   An unforeseen occurrence, which may or may not derive from a failure, and which requires compensatory action.

FAILURE   The off-nominal performance of a component, element or system, regardless of severity.

PAVING   Any preparation of a substrate to facilitate mobility or other activities.

ROBOT   Any machine which extends physical human capability.

SITEWORKS   Landform constructions done with or to native material.

SUPERVISED AUTONOMY   A robotic control mode in which the machine performs detailed task planning and execution, and processes raw sensor data, in response to and in support of intermittent, more abstract human commands.

TELEOPERATION   Strictly, the direct control of a robot by real-time human driving.

TELEPRESENCE   The virtual participation of humans in remote robotic activity, through sensors, communication links, and manipulators.

TELEROBOTICS   The use of supervised autonomy, backed up by tele-operation when required.

LIST OF ACRONYMS

ACS	attitude control system
AFL	after the first cargo landing
AI	artificial intelligence
AIF	airborne inhabited fighter
A & R	automation and robotics
A&R/HP	automation and robotics / human performance
ARC	NASA Ames Research Center
ATC	automated task control
AUF	airborne uninhabited fighter
AUT	airborne uninhabited transport
BA & E	Boeing Aerospace & Electronics
BAO	Boeing Aerospace Operations
BFO	blood-forming organs (bone marrow)
CAD	computer-aided design
CARD	Computer-Aided Remote Driving
C/C	carbon/carbon
CCD	charge-coupled device
CELSS	controlled ecological life support system
DC	direct current
DDT & E	design, development, test & engineering
DLC	diamond-like carbon
DoD	U.S. Department of Defense
DoE	U.S. Department of Energy
DOF	degrees of freedom (for manipulators, the number of joints/separate motions)
EB	electron beam
ECLSS	environmental control & life support system
EM	electromagnetic
EMU	extravehicular mobility unit (spacesuit)
EOL	end of life
EPS	electrical power system
ETO	Earth-to-orbit
EVA	extravehicular activity (spacewalking or Moonwalking)
FOD	fractional orbit direct
GCR	galactic cosmic rays
GF	ground fixed
GM	ground mobile
GPR	ground-probe radar
Gr/Ep	graphite/epoxy
GRS	gamma ray spectrometer
HIP	hot isostatic pressing
HLO	high lunar orbit
IR	infrared
ISRU	in-situ resource utilization

IVA	intravehicular activity
KSC	NASA Kennedy Space Center
LEO	low Earth orbit
LLO	low lunar orbit
LLOX	lunar liquid oxygen
LM	Apollo Lunar Module
L1	Lagrange libration point between Earth and Moon
L2	Earth-Moon system Lagrange libration point beyond lunar Farside
LOR	lunar orbit rendezvous
LOX	liquid oxygen
LRV	Apollo lunar roving vehicle
MLI	multi-layer insulation
MLOX	Martian liquid oxygen
MTBF	mean time between failures
NASA	National Aeronautics and Space Administration
OEXP	NASA Office of Exploration (Code Z)
ORU	orbit (or space) replaceable unit
PFTE	polyfluorotetraethylene (e.g. Teflon®)
PV	photovoltaic
QD	quick disconnect
R & P	rack and pinion
R & R	remove and replace
RF	radio frequency
RFC	regenerable fuel cell
RMS	remote manipulator system (manipulator arm)
RTG	radio-isotope thermoelectric generator
SAA	Special Assessment Agent
SF	spaceflight
SPE	solar proton event (solar flare)
SPS	solar power satellite
SSF	Space Station Freedom
STS	Space Transportation System (shuttle)
TABI	tailorable advanced blanket insulation
TCA	task control architecture
VCS	vapor-cooled shields

LIST OF FIGURES

1. INTRODUCTION AND SUMMARY

1.1 STUDY OBJECTIVES

This report, <u>Robotic Lunar Surface Operations: Engineering Analysis for the Design, Emplacement, Checkout and Performance of Robotic Lunar Surface Systems</u>, presents the results of a study conducted for NASA Ames Research Center (ARC), specifically the Office of Exploration (OEXP) Special Assessment Agent (SAA) for Automation and Robotics / Human Performance (A & R / HP). The core of this study team had performed a study in 1988, reported in 1989 as <u>Engineering Analysis for Assembly & Checkout of Space Transportation Vehicles in Orbit</u>, (the "Orbital Assembly Study" hereafter) to conceive and evaluate a scenario for processing manned, interplanetary spacecraft in low Earth orbit (LEO). The fundamental goal then was to identify options which avoided the need for large processing crews in LEO emulating those at Kennedy Space Center (KSC). At the conclusion of that first study (which revealed high potential leverage for applying state-of-the-art A & R technology), OEXP decided to address, in a similar study to a similar level of detail, the analogous problem of activating planetary surface facilities without reliance on large surface crews. The intention was thereby to form a more complete picture of the exploration mission operations problem before delving into deeper levels of engineering detail.

Stated concisely in the original Statement of Work, the study objective was to: **examine options for (and characterize the benefits and challenges of) performing extensive robotic site preparation of planetary base and scientific sites, and lunar and Mars propellant production facilities.** Lunar applications were the designated priority. As resources permitted, the study would:

1)   Consider alternative designs and scenarios which permit extensive site preparation for buildings and infrastructure construction, mining, digging, habitats, instrument installation, reactor placement, and landing site establishment.

2)   Assess the feasibility of robotic and operational assumptions in lunar observatories and Mars surface missions.

3)   Examine the feasibility of using robotics for the establishment of automated liquid oxygen (LOX) production on the Moon and Phobos.

1.2 STUDY LOGIC FLOW

The study was conducted by Boeing Aerospace and Electronics in Huntsville, assisted by Boeing Aerospace Operations (BAO) at ARC in Mountain View, and with subcontracts to CAMUS Inc., RedZone Robotics and David Akin. Jack Lousma (Skylab and former Shuttle astronaut), Gerald Carr (Skylab astronaut), and Harrison "Jack" Schmitt (geologist and Apollo 17 astronaut) supported the study through CAMUS. Professor William "Red" Whittaker (roboticist) and Lee Bares (civil engineer and roboticist) supported the study through RedZone. Rolfe Folsom and Robert Koch (reliability engineers) supported the study at BAO. The BA&E effort was conducted by Gordon Woodcock, Brent Sherwood and Patricia Buddington. The logic flow shown in Figure 1-1 indicates the task allocations among the various participants.
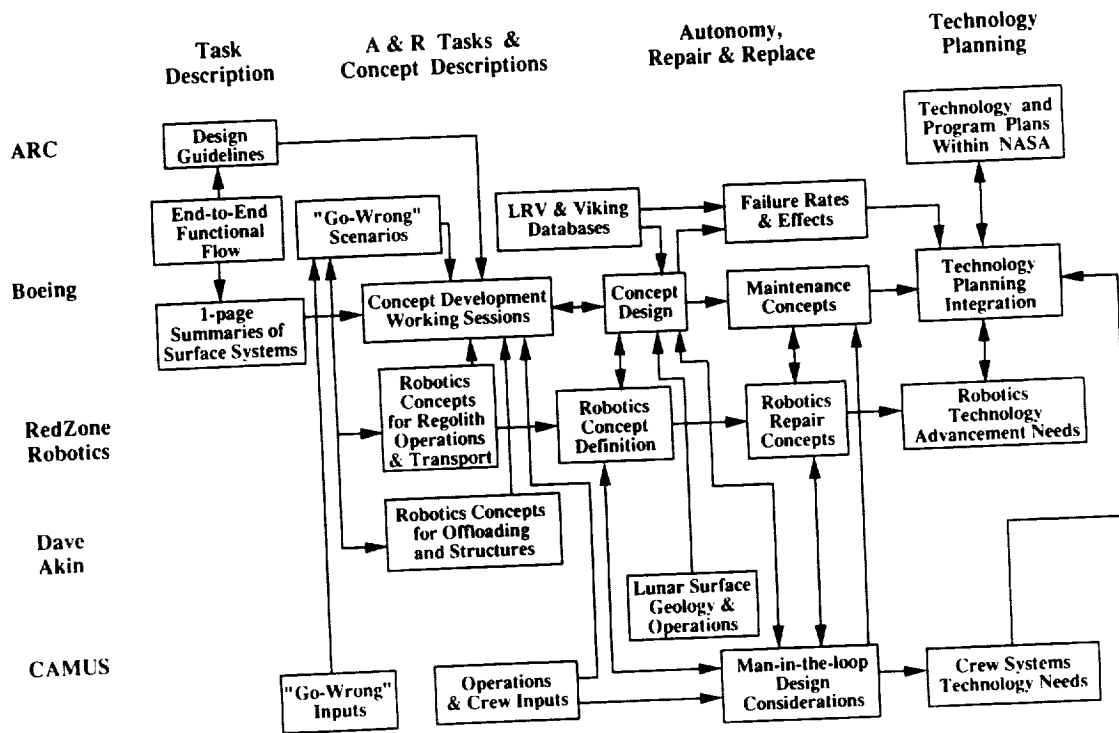
Figure 1-1 *Study task logic flow shows relationships among study participants.*

1.3   HIGH-LEVERAGE ROBOTIC LUNAR ACTIVITIES

A & R has found its most critical and successful applications in repetitive, remote or hostile environments: in factories; on land, under the sea, or in space; in hazardous terrain, or settings lethal or inaccessible (or both) to humans. A & R has been used with great success for initial scientific investigations on other planets. Planetary surfaces are at once hostile, remote and exceedingly interesting; both more complete scientific investigation and eventual settlement of these places would seem to depend on many types of machines to supplant, or extend the capabilities of, people. In this report, we refer to all such machines as robots, and the endowment of robots with the capacity for independent action as automation.

Permanent human presence on the Moon is challenging to bootstrap. We need facilities on the Moon to support the people, but we would seem to require people to construct the facilities. It is certainly possible to devise incremental operations scenarios to resolve this dilemma, but they require off-nominal circumstances. For example, expecting an initial crew to set up a permanent radiation-sheltered habitat on the lunar surface requires either: relying with no backup on an unproven temporary sheltering scheme if a solar flare occurs before set-up is complete; accepting the risks and programmatic effects of the crew aborting to their orbiting, shielded transfer vehicle; or accepting the performance penalty of burdening their lander with a heavy storm shelter. Incidentally, neither approach avoids the need for large, strong robots (whether "driven" or autonomous) to do the construction, nor the cost in lunar surface crew time to perform and oversee the task. Similarly, waiting to begin production of LLOX propellant (the heaviest single component of cryogenic spacecraft and therefore a prime candidate for ISRU) until a large local crew can get the production going, precludes economic payback early in the manned program. LLOX use should optimally begin within just a few years of the first landing; pushing the return farther into the future is prohibitive for private investment and costly for governmental programs.

We are thus motivated to see how much of the emplacement, checkout, startup and maintenance work can be done using A & R. If ways can be found to endow the machinery any lunar development scenario needs with the capacity for reliable, remote operation in the demanding lunar environment, then operational and economic benefits will accrue to the program. Optimally, crews could arrive at an already functioning lunar base;

surface basing of lunar landers could begin early. The first few crew visits would consist of inspecting and troubleshooting equipment, and implementing corrective adjustments, rather than performing marathon, first-generation construction work. In a continuing scenario, routine maintenance, base growth and even scientific investigation would then be able to benefit from an optimal, verified mix of machine and human skills. Extravehicular activity (EVA) time would be reduced, and crews could devote their valuable time to problem solving, process improvement ("tinkering"), experiment design and interpretation. On the Moon as on Earth, "the right tool for the right job" will be essential for timely, reliable, effective achievement. Robots with some autonomy, workpieces made to be handled by them, and people for the thinking and dextrous work that people do best, proffer great potential for comprising the right tools and the right jobs. Complementing human crews with autonomous and supervised machines can qualitatively upgrade the human role on the Moon, maximizing technical and social returns from the program. Instead of the crew being on the Moon for the base (to build it and keep it going), the base will be on the Moon for the crew (as a tool to extend human presence into the solar system).

1.4 STUDY GUIDELINES

Study guidelines were simple:

1)   Our earlier Orbital Assembly Study proposed a set of specific system design recommendations which would make equipment conducive to both robotic and human operations. We followed those recommendations in this study when developing equipment and operations concepts.

2)   We maximized opportunities for machine autonomy,   then supervisory control and finally teleoperation, in that order.   We strictly minimized the onsite presence of human crews for the purposes of this reference scenario.

3)   We presumed 4 lunar landings per year, including manned and unmanned flights. This was a "guideline" since base growth was seen to be open-ended and not subject to physical time constraints like interplanetary trajectories.

4)   The reference lunar lander could deliver 30 t of cargo to the lunar surface and return itself to low lunar orbit (LLO), or land up to 8 crew with supplies for 30 d and return them to LLO.

5)   Lunar operations would focus on establishing the base infrastructure, emplacing and shielding a habitat system, and beginning in-situ resource utilization (ISRU).

6)   Surface power would be baselined as solar, not nuclear, if possible.

7)   The study would concentrate on the lunar case. Investigating additional complexities introduced by extending the operations concepts to Mars would focus on highlighting salient differences between the similar lunar and Mars cases.

8)   The work remained cognizant of changing overall emphases in the Code Z FY89 study cycle, and contributed to them, including President Bush's Lunar/Mars Initiative.

1.5   A & R PERFORMANCE GOALS

The study team members agreed upon several specific goals at the beginning of the study. For a lunar base, A & R systems should:

1)   Offload, possibly move, and service lander vehicles.

2)   Perform necessary site reconnaissance and preparation.

3)   Excavate, beneficiate and transport native lunar regolith.

4)   Install necessary site utilities like power cables, fluid lines and roads.

5)   Construct a landing facility with blast-debris countermeasures.

6)   Emplace and shield with regolith a habitat system capable of later growth.

7) Deploy a modular solar / regenerable fuel cell (RFC) power plant.

8) Emplace and operate a chemical plant to produce LLOX.

9) Perform remove-and-replace (R & R) maintenance on all base elements.

10) Operate reliably in the lunar environment with minimal need for onsite crew.

Performance goals for establishing a human presence on Mars are similar, because the tasks required are quite similar and the environments are somewhat similar. Some elements for a Mars base would be different in detail from those appropriate for the Moon, but setting up, activating and maintaining the base would involve analogous tasks. However, additional environmental considerations introduced by Mars would complicate operational requirements somewhat. Section 4 outlines the issues of resource utilization, communication delays, and contamination for Mars surface operations.

1.6 STUDY APPROACH AND DECISION RATIONALES

Our method engaged an iterative cycle:

1) **identifying requirements** for surface operations, using pre-existing base element concepts where applicable;

2) **designing solutions** which applied A & R techniques optimized for planetary surface environments to workpieces optimized for A & R manipulation;

3) **analyzing the performance** of the developed scenario by assessing its operations schedules, logistics requirements, reliability, failure modes and contingency options, and its interaction with human crews stationed on the Moon, in LEO, and on Earth; and

4)   **targeting future work** by identifying critical or promising directions for technology development and further study.

The specific tasks completed were to:

1)   Identify the function of an initial lunar base

2)   Define the necessary base elements

3)   Define the base site plan

4)   Determine the base construction and operations requirements

5)   Determine the robotic operations

6)   Define the robotic equipment

7)   Determine the sequence of base construction and operations

8)   Develop supporting manifests

9)   Determine appropriate crew roles

10)   Estimate equipment failure rates and workarounds

11)   Identify differences required for Mars application

Such a set of tasks could easily lead to an elaborate, complex catalog of surface system elements, and has done so in the past, even without an emphasis on A & R. Instead, **our study philosophy was guided by two principles: simplicity and design integration.** Our intent was to produce feasible concepts for applying A & R to the very earliest stages of lunar development, that is, for a lunar base program which

begins flights near the turn of the century. We therefore aimed for solutions within the near-term state-of-the-art. However, we were aggressive in thinking about what the near-term state-of-the-art really is; in some instances we adopted technical solutions that might be considered novel. We relied mainly on well-understood technologies and those assured of being available. We considered robotics technologies now in use, or in advanced development for terrestrial applications, to be "available". This principle of simplicity, although it misses the potential of many interesting and promising new ideas, instead lends the credibility of a "proof-of-concept", and permits developing a well-integrated scenario.

Conclusions about solution merit are impossible without extensive tradeoff analyses. Since this study had resources to develop only a reference concept, we chose solutions that offered significant advantages based on high-level systems and operational considerations. By bringing to bear a wide range of experts in space systems, construction, robotics, reliability, and spaceflight experience, and by alternating working meetings with technical detailing, the study team was able to perform "discussion trades" and evaluate those high-level considerations. Only the more robust concepts survived in the group consensus, which thus evolved a toughened scenario.

We developed concepts for the base elements (the robotic workpieces) and the robots (the workers) together, iteratively. That is, tasks 2 through 9 above were accomplished simultaneously. This resulted in a more coherent, closely integrated scenario than could be achieved by simple sequential treatments (defining the base elements and only then defining the necessary A & R). Our element configurations, production-throughput values, and operation scenarios explicitly incorporate our proposed robotic capabilities. Furthermore, the robot types we developed, albeit versatile beyond our scenario, grew in turn directly out of specific, identified requirements. Thus our scenario contains a layer of significance beyond the details of its many elements, consisting of the system interdependencies among them.

We selected oxygen production as the primary function of the lunar base for two reasons. First, immediate and potentially high-cost-leverage uses exist for the product: LOX is the oxidizer in cryogenic propulsion systems, and oxygen is required for life support. Second, and for exactly those reasons, LLOX production constitutes the most-studied ISRU proposal for the Moon. Although any base on the Moon would be used for scientific investigations and lunar astronomy, we chose the base location

according to considerations of LLOX production: resource availability and retrievability, and flight mechanics.

Many processes have been proposed for extracting oxygen from lunar minerals. **We selected hydrogen reduction of ilmenite in a fluidized-bed reactor,** primarily because several papers about it exist in the ISRU literature. We anticipated that the purpose of our study (investigating A & R applications to lunar operations) would be best served by taking a second-generation look at a process already familiar to the space exploration community.

Supplying power during the 14 d lunar night constitutes one of the toughest problems of lunar base planning. The traditional choice is between full-time nuclear reactors and elaborate power-storage systems for use with solar collectors. We eschewed the former, in keeping with our guideline of simple, existing or imminent technology. The latter is extremely mass-costly, as even advanced regenerable fuel cell (RFC) specific mass is of order 1 t/kWe for the 336 hr of lunar darkness. That is, it would take about 1 t of complex hardware and reactants to keep 10 100 W bulbs burning throughout the lunar night. To minimize transported mass, we chose an unconventional third option, seemingly practicable for an early lunar base: **we use solar power exclusively (with RFCs for life-support and equipment-keep-alive power), and mostly shut the LLOX industry down during lunar nights.** Thermal cycling may negatively affect LLOX production process plant reliability (on the other hand, gas-process plants are constrained to some degree of batch-processing anyway by the lunar vacuum). In addition to mitigating the power-storage problem, operating the base according to the lunar diurnal cycle naturally accommodates periodic offline inspection, maintenance, planning and data reduction, and even unrelated activities like astronomy.

Humans outside the Earth's atmosphere and magnetic field require shielding against continual galactic cosmic rays (GCR) and sudden, unpredictable solar proton flares (SPE). Materials differ in their shielding effectiveness, but large amounts of mass are required in any case to enclose large volumes with shielding. It is generally accepted that lunar shields can be more economically configured by filling comparatively light forms with lunar regolith, than by transporting entire shields from Earth. The acceptable radiation budget for astronauts is greater than that for the general population (Figure 1-2). Recent work presented at the 9th Space Manufacturing Conference indicates that these standards can be
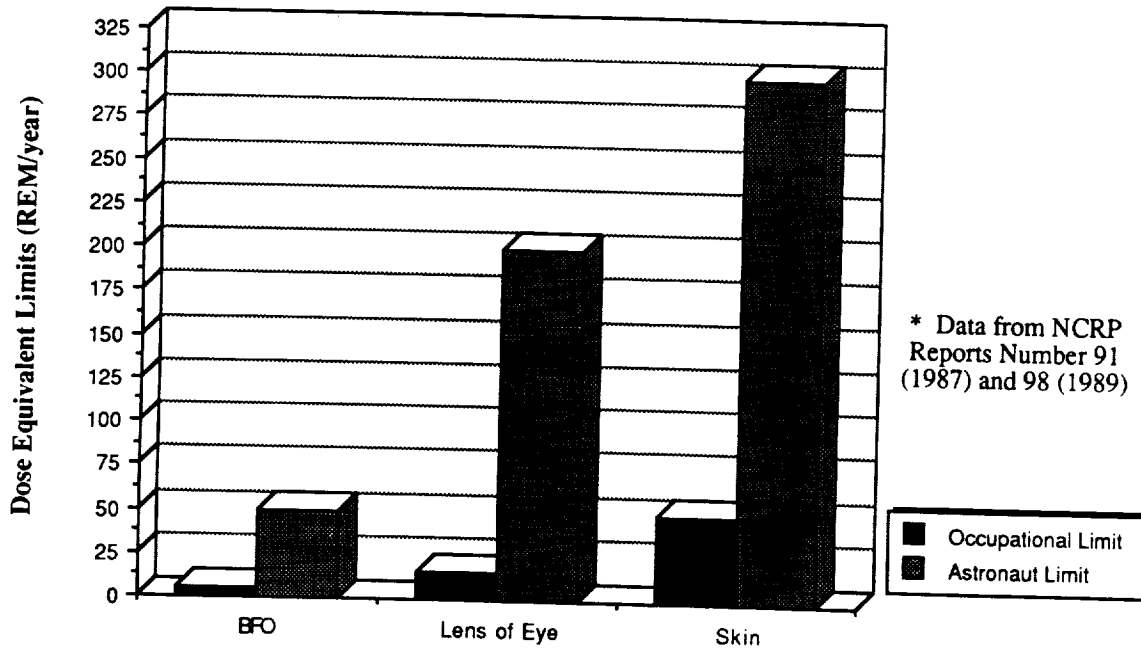
Figure 1-2 *Astronaut radiation dose limits exceed those for the general population.*

met inside aluminum habitat modules enclosed by of order half a meter of regolith fill, assuming a bulk density of 1.5 t/m^3. For this study, **we assumed that a 0.5 m layer of uncompacted lunar regolith would be sufficient to provide radiation protection for professional astronauts and mission specialists housed at an early lunar base.**

Direct burial of habitat modules is commonly proposed. This approach is unfavorable for three primary reasons. First, it would complicate the inspection and repair of critical subsystem components located outside the module. For example, the ammonia-carrying secondary coolant loop, and its heat exchanger interface with the water primary loop, are located outside the module for safety. Even locating these components outside the radiation shield could not prevent burying connectors. Second, direct burial would interfere with habitat expansion as the base grew. In early stages, this should be accomplished simply by attaching more modules, delivered from Earth, to docking adapters built into the system. Finally, re-excavation of directly buried modules for any reason (growth or maintenance) would have to be more like an archeological dig than construction, because of the relative susceptibility of the thin-walled modules to puncture damage. Scenarios in which modules are covered over by bulldozers and then forgotten are quite

unrealistic. Unavoidable activities of inspection, maintenance and alteration must be facilitated. **We mandated 2 m clearance between module exteriors and radiation shielding, and no direct burial; instead we required construction of a separate shelter structure around the habitat system.**

1.7 SUMMARY OF FINDINGS

Layout, buildup, checkout, startup, operation, monitoring, and maintenance changeout activities for an initial, industrial planetary surface base appear feasible largely robotically. Advanced levels of automation can reasonably be baselined into conceptual base scenarios to control and execute many operations in these task categories. LLOX production appears feasible using only daytime solar power. Within 3 yr of the first cargo landing, LLOX production can begin at a rate of order 100 t/yr (sufficient to tank four lunar landers per year). An expandable habitat system can be emplaced and shielded before the first human visit. Appropriate A & R capabilities can be implemented safely and reliably in the man-rated context of a base, and in fact can strongly enhance the overall safety environment for humans in a hostile planetary setting.

The right robotic devices can reduce direct physical risks to crews by acting as reach extenders and force multipliers. Such machines are strictly required for several identifiable tasks around a planetary base that a suit-clad astronaut simply cannot do, and desirable for many others as well. Robots may reduce the risk of damage to hardware, because they can be capable of controlled, slow, precise, refined positioning and manipulation. For well-characterized activities, robots can enhance efficiency by permitting untiring, repetitive, continual work.

The right control architecture can further reduce risks to human crews by minimizing the need for EVA to control working robots. Hierarchical, supervisory software can reduce the IVA human workload as well by allowing the machine as much self-control as it can handle for a given task, subject always to human command intercession. (Even greater autonomy is enabling for complex Mars robots, since the feedback loop with Earth can take most of an hour to close.) Much of the task planning and engineering analysis for early planetary operations can be exported to Earth. Relieving

onsite crews of this substantial operational burden leaves them more able to apply human capacities to solving non-routine problems. Finally, an appropriate control structure can automatically produce a detailed, complete record of all actions taken and data sensed, augmenting the maintenance expert-system knowledge base and enhancing program success.

The challenging problem of dirty planetary environments can apparently be met with a combination of prudent design, modern materials, and adequate attention to spares logistics. Some subsystems, like all-metal vehicle wheels and hot electronics, require technology development work to validate them for long- life performance. Our first-generation reliability analysis of lunar base elements indicates that the necessary maintenance activity can be accomplished within our proposed operations schedule, and that crews will have plenty to do during lunar nights. 15 % of the active component weight is an appropriate spares budget for systems studies. We have begun to indicate component types most likely to fail. Electronics are expected to be particularly degraded by thermal cycling on the Moon.

The A & R capabilities baselined by this study do not depend on breakthroughs in fundamental science, but do require both extensive engineering development and space-qualification of capabilities already available in some terrestrial industries. The integrated, simultaneous, hierarchical control of a fleet of mobile robots needs to be demonstrated, and hardware concepts require validation in surface-environment analogs. Embedding and integrating a virtually complete self-diagnostic ability into base equipment appears to represent the most challenging development, albeit one that surface systems will share with advanced spacecraft and complex terrestrial industries. Technology advancement activities should be stepped up now, and targeted to address specific lunar problems, to support A & R surface operations around the turn of the century. Most issues can be addressed in distributed fashion, with individual laboratory research efforts.

The onsite crew presence baselined by this study (2 flights out of 15) should be taken as a theoretical minimum. Good reasons exist to believe both that more frequent crew visits would be advantageous ("eyeballs-on" verification, workaround implementation, process adjustment), and that a real lunar development program would mandate crew-carrying flights at least once a year throughout the buildup. The current Lunar/Mars Initiative reference has virtually as many manned flights as cargo flights to the Moon, and twice as many crew flights as cargo flights to Mars. Our purpose here was to

investigate strict technical requirements for crew intervention in predominantly robotic activities. The effort required to set up, operate and maintain a planetary base tends to exceed conventional expectations. In a non-A & R scenario, these activities would dramatically reduce the crew time available for investigative efforts. Our reference scenario posits an efficient maintenance scheme in which defective parts are robotically replaced with spares, and robotically brought inside a pressurized workshop, where human crews can clean, unseal, evaluate and repair them for further use. IVA repair work, EVA inspections, and science and process investigations then comprise the bulk of surface crew responsibilities.

Principal Findings for Surface Issues:

1)   A detailed three-dimensional sitemap, including subsurface characterization with 10 cm resolution, is important for predictable robotic surface operations, and informed base layout.

2)   The excavation and beneficiation required by site preparation dominate the requirement for generating LLOX plant feedstock during base buildup. Establishing the base infrastructure produces over a year's supply of feedstock.

3)   Heavy work (mining, and habitat system construction) uses creeping speeds (from 30 cm/s down to barely perceptible motion) which tend to be incompatible with direct human operation (because they are so slow), but are highly amenable to robotic control.

4)   High-power (> 10 hp) vehicles are not necessary for an early base to produce LLOX at 100 t/yr rates.

5)   Three vehicle types (a light, crew-adaptable rover; a medium, high-reach truck; a large, robotic mobile crane) appear to constitute a minimal but sufficient set. All seem widely useful beyond the baseline scenario.

Principal Findings for Space Transportation Issues:

1)   The lander cargo capacity fundamentally affects base element design, as it determines the largest unit transportable intact to the surface.

2)   One flight every three lunar cycles (4/yr) is appropriate early in the base buildup, but an ability to mount more frequent flights could avoid excessive downtime later, and utilize more fully the redundant robotic systems. Flexibility in the launch schedule can enhance surface efficiency and scenario reliability.

3)   15 30 t flights are required for the scenario: 7 for the LLOX industry
                                                        3 for the habitat system
                                                        3 for mixed-use equipment
                                                        2 for manned checkout

1.8 ROADMAP OF FINAL REPORT

Although we developed the element concepts, robotics concepts, and operational analysis simultaneously as described above, for clarity we present our results in a distilled fashion in this report.

Section 2 explains in detail the reference element concepts we designed for our study of robotic lunar surface operations. These represent the physical work environment within which all base activities must take place, and comprise an accounting of the essential parts of a complete lunar base. Section 2.1 describes the largest scale of design, the base site plan. Section 2.2 explains the primary, fixed base element concepts. Section 2.3 discusses the utilities required to connect and enable the primary elements. Section 2.4 describes the infrastructure, such as roads, built from local materials. Section 2.5 details the mobile robot concepts developed to operate at the reference lunar base.

Section 3 reports analyses which led to the integrated concepts, which justify their details, and which examine their combined performance. Section 3.1 explains quantitative requirements for building up the base, and the sequence by which it is accomplished. Section 3.2 shows how and when the necessary equipment is brought to the Moon. Section 3.3 supports the mobile robot concepts with detailed explanations of the required technologies and control methods. Section 3.4 describes current terrestrial robotics applications which argue for the feasibility of advanced lunar robotics. Section 3.5

outlines the range of contingency scenarios factored into the integrated concept. Section 3.6 defines appropriate and required crew roles in a robotically-operated lunar base. Section 3.7 details machine design approaches for dealing with lunar environmental complications. Section 3.8 reports a quantitative reliability analysis of the primary and mobile base elements. Section 3.9 discusses reasonable approaches to supplying spare parts. Section 3.10 explores the versatility of the reference equipment concepts beyond the baseline scenario. Section 3.11 describes stages of base growth into the future beyond the initial scenario.

Section 4 briefly outlines the salient differences between the cases of robotic operations on the Moon and on Mars, to establish a starting point for future work.

Section 5 lists and discusses recommendations for future thinking and work, based on the results of this study. Section 5.1 consolidates specific suggestions from the study participants for improvements in the reference scenario. Section 5.2 highlights issues requiring consideration in the development of robotic operations scenarios. Section 5.3 identifies specific technologies needing development before a scenario like the reference can be accomplished.

Section 6 concludes the report.

Section 7 contains a bibliography of background, source and related references.

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2. LUNAR BASE ELEMENT CONCEPTS

In addressing the problem of applying A & R techniques effectively to lunar base operations, we discovered two early complications. First, no end-to-end systems analysis and operations scenario for emplacing an initial lunar base had ever been published. So to develop detailed task schedules and consistent execution-time analyses, we first had to develop an integrated lunar base reference concept. Second, even simply assembling a base concept from pre-existing element concepts was impractical, since the various published element concepts had not been designed with A & R specifically in mind. Incorporating A & R considerations post facto into such base element concepts proved less practicable than it had for interplanetary exploration vehicles in the Orbital Assembly Study. The resulting operations scheme would have been artificially and needlessly complex.

Consequently, a major task of this study became the activity of designing an integrated lunar base reference concept, useful for detailed analysis of A & R operations. The chief liability of such a basic approach is that the study resources could not permit extensive tradeoff analyses to be performed to refine and support it. The reference concept is therefore a point design. The chief advantage was that it enabled us to develop the A & R concepts together with the elements on which they were required to operate. The various facets of the operations scenario are therefore closely integrated. We consider that the value of our scenario resides not so much in details of the many elements as in the system interdependencies among them. The requirements and functions we identified must be accommodated (in some fashion) by lunar operations schemes, even if not in the particular ways we selected. So although our scheme included A & R embedded from the beginning, it is useful for general lunar base studies.

Figure 2-1 contains a concise listing of the primary, mobile, utility and sitework infrastructure base elements developed for this study.

Primary Elements	Landers (up to 3)	(cryogenic, 30 mt landed capacity, manned or unmanned)
	Habitat System	(habitat module, 2 airlocks, connecting node w/ cupola, pressurized workshop)
	Radiation Shelter	(regolith - filled, encloses hab system, provides unpressurized garage)
	Solar Arrays (24)	(20 kWe, deployable rigid tracking)
	Regenerable Fuel Cell Modules (2)	(nighttime power, 20 kWe output, 50 % overall efficiency)
	Oxygen Reactors (3)	(batch fluid - bed, hydrogen reduction of ilmenite)
	LLOX Depot (1 per pad)	(liquefaction, refrigeration, redundant storage, pumping)
Mobile Robots	Straddler (2)	(robotic mobile gantry; lifting, moving, positioning, mining)
	Truck (2)	(outrigger - stabilized, high - reach boom w/ utility suite, front loader, rear tow with utility trailer suite, robotic w/ onboard operator station)
	Rover (2)	(light duty, site survey & crew transport, robotic or manned)
Utilities	Radiator Modules (8 total)	(5 and 3 ganged together, with fixed, deployable sunshades)
	Debris Barriers (12 / pad)	(deployable, intercept ejecta from lander exhaust to protect base elements)
	Hoppers (22)	(with chutes, hold 27 t material each)
	Storage shed (optional)	(made of habitat shelter vault sections)
	Guidance Beacons	(lander targeting and local site navigation)
	Communication Transceivers	(link all mobile elements, and site to LLO and LEO)
	LLOX terminal (1 / pad)	(buried valve box and conditioning - umbilical connectors)
	Gas Lines	(conduct gaseous oxygen from reactor field to depot)
	Liquid / Vapor Lines	(connect depot to LLOX terminal under landing pad)
	Power Substation	(regulates industrial load and crossover distribution to hab power system)
	Power, Data & Grounding Cables	(throughout site, linking all fixed elements)
	Sensor Heads	(monitor critical views)
	Local Lights	(augment Earthlight during lunar night for critical areas)
	End Effectors & Tools	(for robot manipulators and crew)
Siteworks	Spaceport	(up to 3 landing pads w/ prepared surface)
	Foundations	(undisturbed, naturally consolidated regolith, 1 m overburden scraped off)
	Open Workyard	(paved area for equipment staging, disassembly and reconfiguring)
	Connecting Roads	(leveled, paved with compacted gravel for dust control)
	Deposition Sites	(receive rocks, gangue, spent oxygen - reactor solids)

Figure 2-1   The lunar base site elements are listed in four categories.

2.1 SITE PLAN

Our prospective site is on the southern edge of the Sea of Tranquility (on the equator, about 27° east longitude, between the craters Moltke and Maskelyne. This location appears highly suitable for an early, oxygen-producing base for a variety of reasons.

Apollo 11 sampled the regional geology directly: mature, flat, deep regolith, rich in ilmenite. Mature regolith is well comminuted. The surface layers of basaltic flows comprising lunar maria have been broken up, weathered, mixed, and shaken into compaction by major impacts and billions of years of micrometeoroid gardening. The result is a rather homogeneous blanket of soil, (with admixed stone and rocks), as deep as 30 m in some regions. The composition should become rockier with increasing depth, finally blending into a blocky interface between overlying regolith and underlying basalt. The surface topography is flat compared to lunar highlands, and the regolith is thought to contain generally between 7 and 10 % by weight of ilmenite.

The surficial nature of the regolith layer, and the non-concentrated presence of ilmenite within it, indicate some form of strip-mining and processing of relatively large amounts of regolith will be required. For this type of extraction operation, mare sites are the best we know of on the Moon. The largely predictable character of the native material is expected to facilitate mining operations, and is an integral feature of our design response.

Of potential mare sites, the equatorial, southern Sea of Tranquility is most favorable astronautically. It is most energetically accessible from lunar equatorial parking orbits. Furthermore, a Nearside equatorial site is essential for efficient ballistic transportation of large amounts of lunar resources to L2, a likely eventual orbital staging point. Should an initial oxygen-processing base in the Sea of Tranquility grow to be a vital supplier of liquid oxygen to orbital staging points for other missions, a mass-driver could be accommodated.

Finally, the chosen site's Nearside location permits continual communications with Earth orbit, but is still fairly close to the limb. That would facilitate eventual construction of a ground transportation link with other base sites near the limb on Farside, established for astronomical purposes.

The reference site plan was developed in conjunction with the base element design effort, following standard practice. The elements were identified (Figure 2-1), characterized, sized and tallied; their interdependencies and interferences were assessed along with any special positioning and orientation requirements; these data were recorded in a proximity diagram (Figure 2-2), from which the site plan was directly generated (Figure 2-3).

The site plan is clustered around an open workyard. An expandable spaceport complex is on the east side, the direction from which landers approach along a shallow glide path (nominally 15° above the horizontal). Resource processing (the base "industry") is to the north. Power production is to the west, most remote from the debris-producing spaceport. Human habitation is to the south.

In general, locations were governed by future growth, while proximities were governed by minimizing infrastructure and operations costs. For example, grounding cables must connect all base elements (on the Moon, only common "chassis" grounding appears possible because of the anhydrous regolith) to prevent potentially hazardous

North

Spaceport growth

Industrial growth

Power
growth

Wilderness

Habitation growth

Spaceport growth
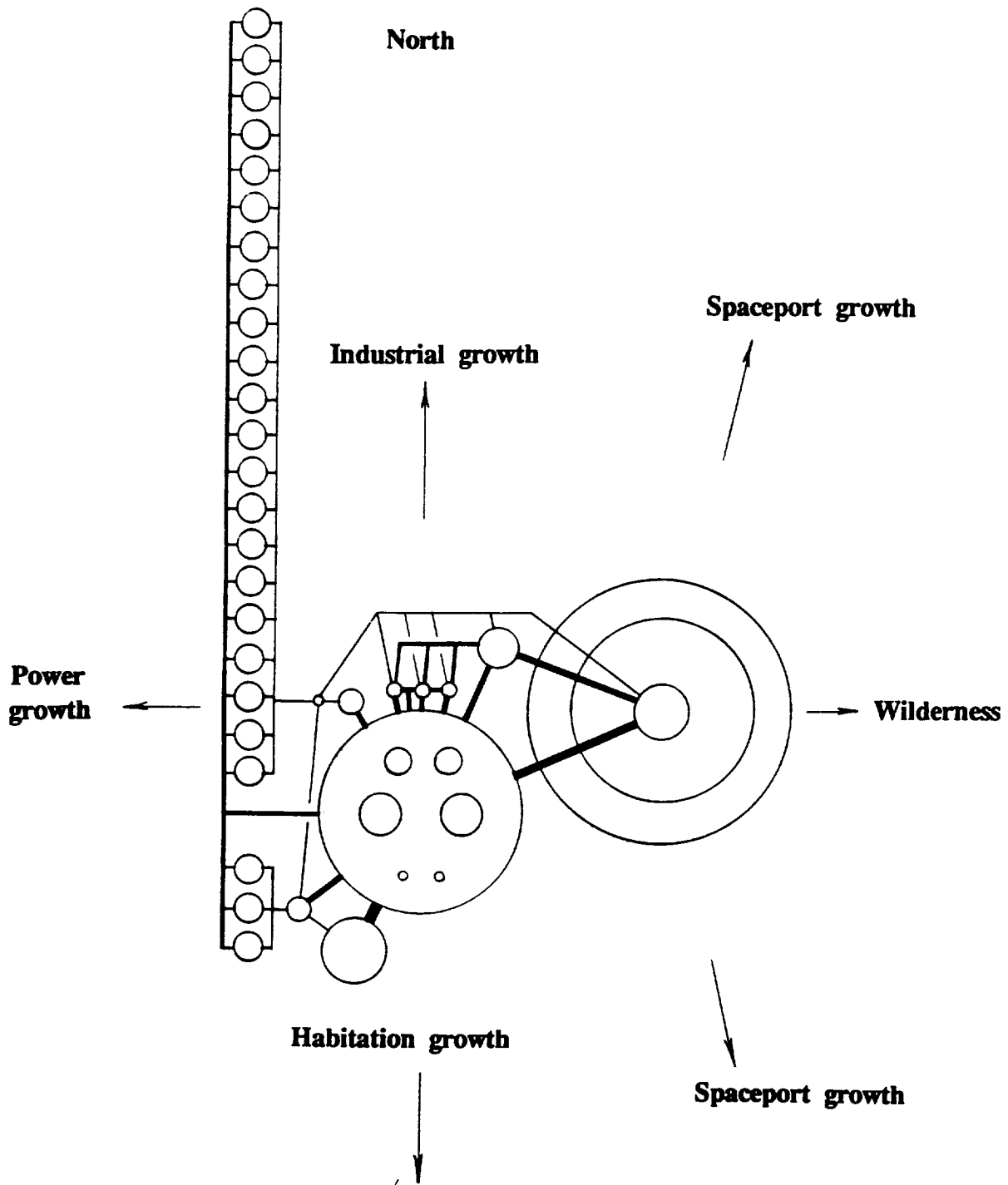
Figure 2-2 *A proximity diagram records the sizes, and functional interconnections among, the base elements.*

50 m

North

Industrial Power Plant

RFC Module

Power Substation

Oxygen Reactors

Service Road

LLOX Depot

Debris Shields

Paved Pad

Lander

Cleared Pad

Workyard

Spaceport Access Road

Rover

Habitat Shelter

RFC Module

Habitat Power Plant

Truck

Straddler

Pad Access Road
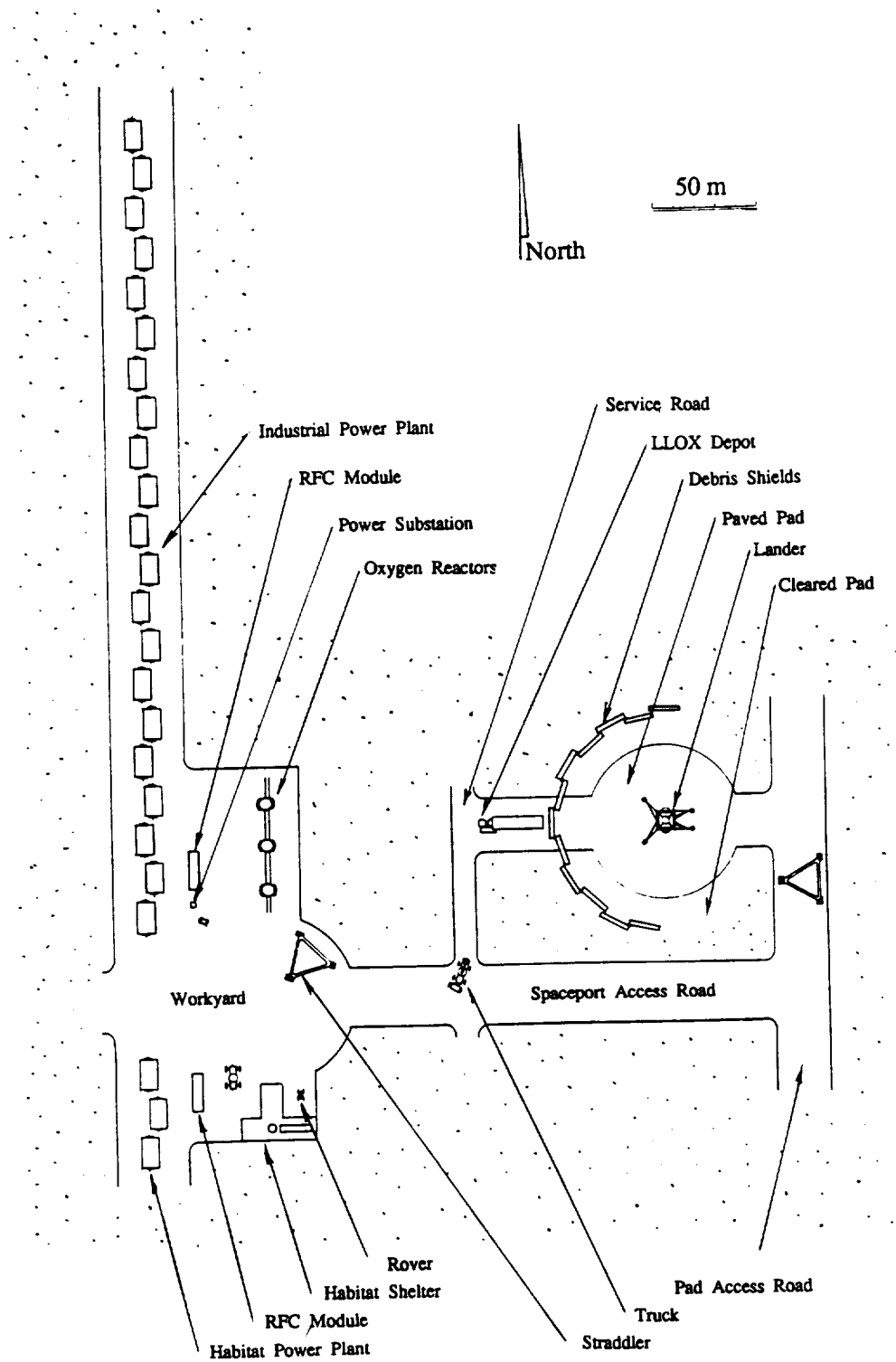
Figure 2-3 *The lunar base site plan shows all primary, mobile and sitework elements to scale, assembled according to the proximity diagram.*

differential charging. But such cables are probably cheaper than cryogenic fluid transfer lines, which may be heavier and bulkier, certainly require more maintenance attention, and introduce the hidden cost of additional refrigeration power per unit length. So keeping fluid lines short and accessible, at the expense of longer grounding cables, is probably a good trade.

Trafficked areas, particularly around sensitive systems, require some surface treatment (generically called "paving" in this study) to mitigate the dust generated by surface transportation and crew activity. Even the "minimal" paving method baselined by this study (and described in section 2.4) consumes such a large fraction of available resources of time, material, machines and energy that limiting it has high operational leverage. Thus a major constraint on the site plan was not just keeping elements as close together as practicable, but minimizing the amount and complexity of paved area connecting them.

Landing pad siting needs to be traded in more complete detail, but operational benefits accrue from the unconventional approach of close proximity. Travel times between the landing pad and other base facilities are dramatically reduced over conventional scenarios which feature kilometer-scale separation. Infrastructure connecting the pad with base facilities, the construction activity required to emplace it, and the continuing activity required to maintain it, are all reduced as well.

Debris is ejected at high velocities when a rocket exhaust plume dislodges surface particles. Although most travels outward virtually horizontally along the ground, the flow does loft some particles. In the lunar vacuum, smaller particles travel farthest ballistically, with some studies showing damaging impingement fluxes many kilometers away from the touchdown point of second-generation (higher weight and therefore higher thrust) lunar landers. Soil erosion can begin with the lander still at altitudes of several hundred meters (and thus up to several kilometers away from the touchdown point horizontally). In the full operational context of an active lunar base, a combined strategy holds the greatest promise. Minimizing debris production (through surface treatment of the pad area), intercepting debris at the source (before particle trajectories attain much height), and protecting critical components like sensor lenses (with covers) and observation windows (with peelable

layers of plastic) costs a little in sitework, hardware mass and design effort. However, it buys greatly simplified surface transportation schedules, reduced roadbuilding and access time in emergencies.

Occasionally, landers may suffer a "hard landing" or outright crash. Chemically propelled space transportation systems historically have success rates in the 95 % class, although landers may have substantially better reliability than launch vehicles (the most critical time occurs after the engines have already been burning nominally, rather than immediately at ignition as with launches). In gauging risk to the base from landing proximity, we must distinguish among failure scenarios. The commonly referenced "error ellipse" is simply the geometrical result of a probability distribution for stochastic impacts, given that along-track velocity exceeds cross-track velocity. The error ellipse is however a tool most reasonably applied at a scale of several kilometers, and so tells us little about detailed base siting. That is, addressing crash risk to the base merely by choosing some arbitrary landing pad separation (a decision which will become a permanent feature, with major operational impact, even though no empirical data would be available for the new system for several years after construction) appears an insufficient resolution. Although further work is called for, there may be good reason to posit a more complex footprint for landing failures (of piloted vehicles using terminal guidance beacons) occuring close to touchdown. For example, overshoots are less common than undershoots for airplanes, as guidance failures tend to produce "short" crashes. And during hover just prior to touchdown (the period of highest risk to local facilities and a regime resembling helicopter landings), a "stuck thruster" could result in a sideways crash, equally probable in any direction. Albeit one of the most likely failure modes, the "stuck thruster" probability is still remote; vehicle designs typically incorporate redundant (compensating) thrusters.

The availability of feasible ejecta countermeasures, and the necessary reliability of man-rated spacecraft, together appear to permit siting the spaceport immediately adjacent to the rest of an initial base. Since approaches are close to horizontal (lofting debris along the way) and departures are essentially vertical, eastern locations are indicated. Base growth would tend to introduce simultaneously both greater crash probability (because of more flights) and greater base/spaceport separation. Section 5 contains recommendations for further siting refinements.

The base site plan is pre-adapted for base expansion, facilitating indefinite growth while minimizing functional interferences as more systems are added. The intention is to capitalize on the substantial site infrastructure investment by avoiding premature refitting, relocation or retirement of base systems. Base growth is discussed in section 3.11. The site plan also yields directly measurable distances and areas, necessary for complete analysis of activity schedules and requirements.

2.2 PRIMARY BASE ELEMENT CONCEPTS

LANDERS - The reference cryogenic lander (Figure 2-4) shuttles between LLO and the base. It can deliver 30 t of cargo to the surface and return itself to LLO, flying autonomously. Alternatively, with the addition of a self-contained crew module, it can deliver from 2 to 8 crew (with supplies for from 30 d to 6 mo), returning them to LLO and flying piloted. A single-stage vehicle, it is originally assembled in LEO from a few, ground-integrated sections, and brought to LLO by the SSF-based, aerobraking transfer vehicle which replenishes its propellants there (Figure 2-5). These transportation vehicle concepts are taken from earlier work (Boeing D615-12002). The 100 t/yr LLOX production rate designed into our scenario is sufficient to refill such a lander's LOX tanks for 4 round trips between the surface and LLO. Once LLOX production becomes regular, the transfer vehicle can begin flying with offloaded, or smaller, propellant tanks. Previous economic analyses have shown that the highest-leverage use of LLOX is in the LLO-to-surface leg of the in-space transportation network. Supplying LLOX back to LEO for transfer usage is marginally beneficial; the benefit depends strongly on the mass of production equipment which must be placed on the Moon to get the LLOX.

The lander has a large (8 m x 8 m), open payload platform, on which can be mounted in mass-balanced fashion the widely varying combinations of payload packages required for building and supplying a lunar base. In the crew-carrying mode, the crew module is mounted on this platform, mass-balanced with logistics packages. The landing leg configuration is an unconventional hybrid of four touchdown points in a triangular geometry, which can be thought of as a tripod with one double leg. This arrangement allows our triangular-plan straddler vehicle to offload itself simply, and then hoist later

Hub Module as payload

Crew Cab (up to 8 crew)

Payload Platform

Frame Structure

3 RL - 10 Derivatives

Thrust Core / Autonomous
Utilities & Guidance

Side Elevation

Front Elevation

5 m

Attitude Thrusters

LO2 Tanks

LH2 Tanks

Landing Footing

Plan

Fixed Landing Gear

Dry vehicle	7.3 mt
LH2 capacity	4.1 mt
LO2 capacity	24.5 mt
Manned payload	13.3 mt down
	6.3 mt up
Cargo payload	30 mt down

Figure 2-4 *The cryogenic lander operates either robotically or with onboard crew.*

Extreme
CM Locations

4 30 klbf
Cryogenic Engines

Lander Cab
Berthed Position

RMS Track

Aerobrake

Access Tunnel

Long Section

Transit Habitat

5 m

Transit Vehicle

Leeward Elevation

LO2 Tanks

FRCI Tile Lip

LH2 Tanks

**Crew
Option**

Structural Frame

Aerobrake
Rib Structure

-- RMS - assisted vehicle berthing

-- Lander fueling with slow spin

-- Crew transfer through pressurized tunnel

-- Logistics - carrier transfer with RMS

Figure 2-5 *The aerobraking transfer vehicle supplies cargo and propellant to the lander in low lunar orbit.*

25

payloads directly off as well (Figure 2-6). The ability to overlay the straddler's and lander's mass centers also simplifies landing the straddlers in the first place, and facilitates their moving grounded landers. The straddler is described in detail in section 2.5.

Figure 2-7 lists the types of maintenance activities for the lander that some degree of surface-basing will impose on base systems and their operation. The trades between surface basing and LLO basing for such a vehicle are incomplete. However, a functioning lunar base with repair facilities and spares does represent a more capable maintenance resource than a transfer vehicle in LLO, and lunar gravity may actually facilitate some maintenance jobs compared to the microgravity environment in orbit. Since lander servicing and conditioning comprise a real functional requirement for the base, we consider the lander to be a legitimate base element.

Lander offloading is one of the thorniest problems apparent for lunar operations. Building up even a small lunar base like our reference, which requires of order 400 t of hardware to be emplaced, clearly requires landers optimized for putting payloads on the surface. However, the mass magnification inherent in lunar transportation architectures levies substantial penalties for any additional inert mass on the lander. One way to look at this is that a kilogram on the lunar surface costs about six kilograms back in LEO; another way is that a kilogram which is part of the lander is a kilogram that isn't payload. So offloading mechanisms mounted on the lander increase operating costs. Furthermore, such devices leave untouched the problem of how to move offloaded payloads around, once they are removed from the lander. Lander-mounted cranes and ramping schemes all suffer in this regard. And the latter typically must accommodate a drop to the ground in excess of 5 - 10 m.

A class of alternative solutions is to configure the lander such that the payload is already near the ground at touchdown. Because this approach requires the payload and engines to be side-by-side, either the payload or the engines must be mounted around the edges of the vehicle. Side-mounted engines require redundant units to maintain balanced thrust in an engine-out contingency. Normally all engines would run throttled, to allow quick, reliable compensation; the failed engine and its opposite would shut down, and the others would increase thrust. This is a non-optimal way to use cryogen engines, and again requires more lander inert mass. Side-mounting, or "splitting", payloads requires evenly divisible payload packages, something rarely (if ever) possible in a real base buildup
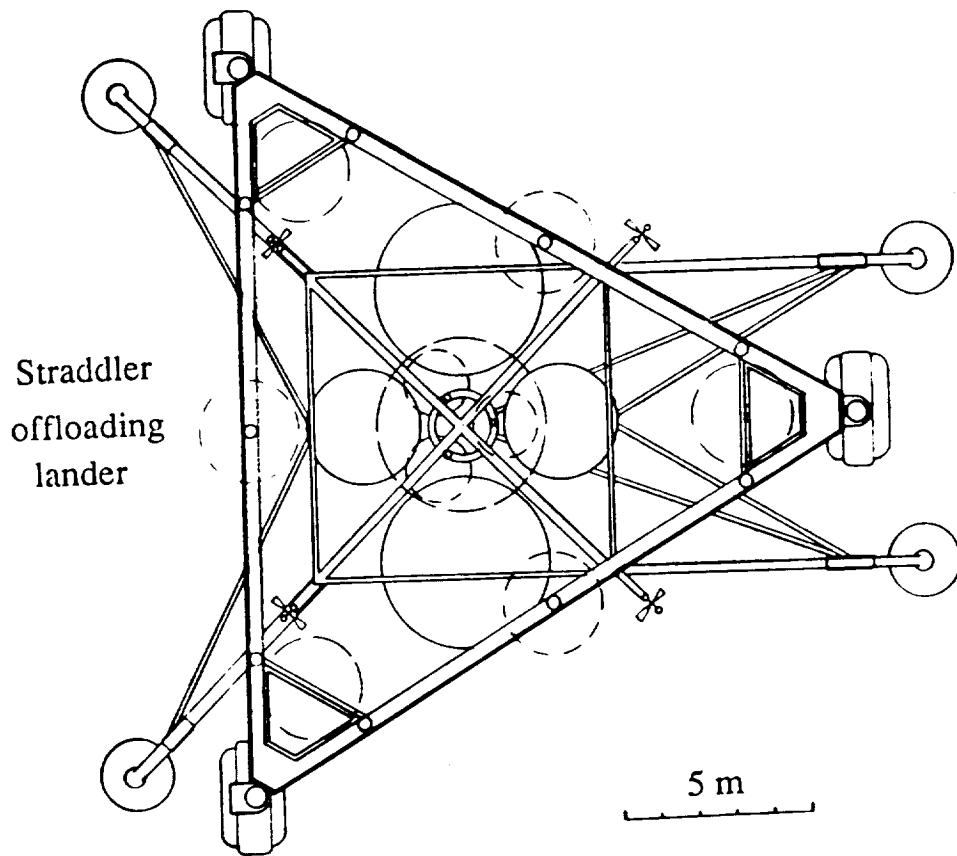
Figure 2-6 *The lander is offloaded simply by the "straddler" mobile robot.*

scenario. Although these approaches may show promise for some unmanned, specialty payloads (like oversize habitat modules for an advanced base), they also avoid the issue of relocating payloads once landed.

Propulsive offloading is another possible approach, which has been largely unstudied. Although it cannot easily accommodate subsequent relocation or precise positioning, and introduces penalties of additional risk, debris damage, and propellant mass, it may be cost-effective, again, for specialized applications. We chose the approach of a top-mounted payload, offloaded by a multi-purpose mobile gantry, because it supported other base requirements so well (detailed later) and because it did not penalize the lander at all.

Access Issues

Visibility
Reach
Mechanical purchase

Activities

Operation
Safing
Simulation
Vent / drain / resupply
Cleaning
Monitoring
Inspection
Testing & checkout
Adjustment
Changeout
Repair
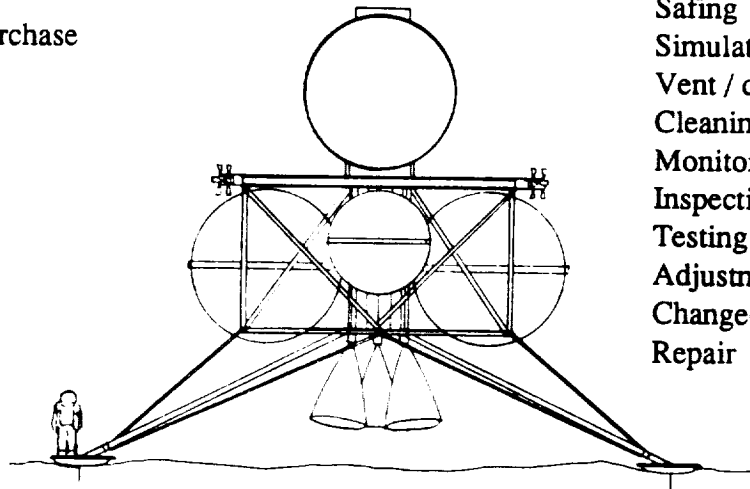
Power System

Cleaning array surfaces
Recoating
Repairing broken connections
Splicing
Component replacement

Sensors & Communications

Visual inspection
Splicing
Remounting
Articulation mechanism repair
Cleaning
Component replacement

Propulsion System

Visual inspection
Leak checks
Mechanical adjustments
Component replacement

Structure

Visual (EM) inspection
Dynamic testing
Jury - rigging
MLI / debris bumper replacement
Deployment mechanism repair
Tether replacement

Thermal Management

Visual and thermal inspection
Radiator surface cleaning
Heat pipe patching & splicing
TPS patching
Seam sealing
Recoating
Component or unit replacement

Figure 2-7 *The lander requires maintenance while at the lunar base.*

HABITAT SYSTEM - The initial habitat system is an expandable set of SSF-derived pressure vessels (Figure 2-8). It is nominally sized for 6 crew for short durations (1 lunar cycle), but could productively house fewer crew for longer stays or larger crews for shorter stays. The system allows redundant ingress and full-site exterior viewing (two requirements evolved from safety and teleoperation considerations), supports IVA science and operations management, and permits shirtsleeve maintenance of modular site equipment. For these requirements, a minimal crew system set consists of: a combined habitat / operations center / laboratory module; two airlocks; a connecting node with lookout cupola; and a pressurized workshop. Internal accommodations would be Spartan for the early, man-tended phase of the base (Figure 2-9). Although untraded, the habitat system shown is adequate for initial operations, and aptly reveals basic A & R tasks.
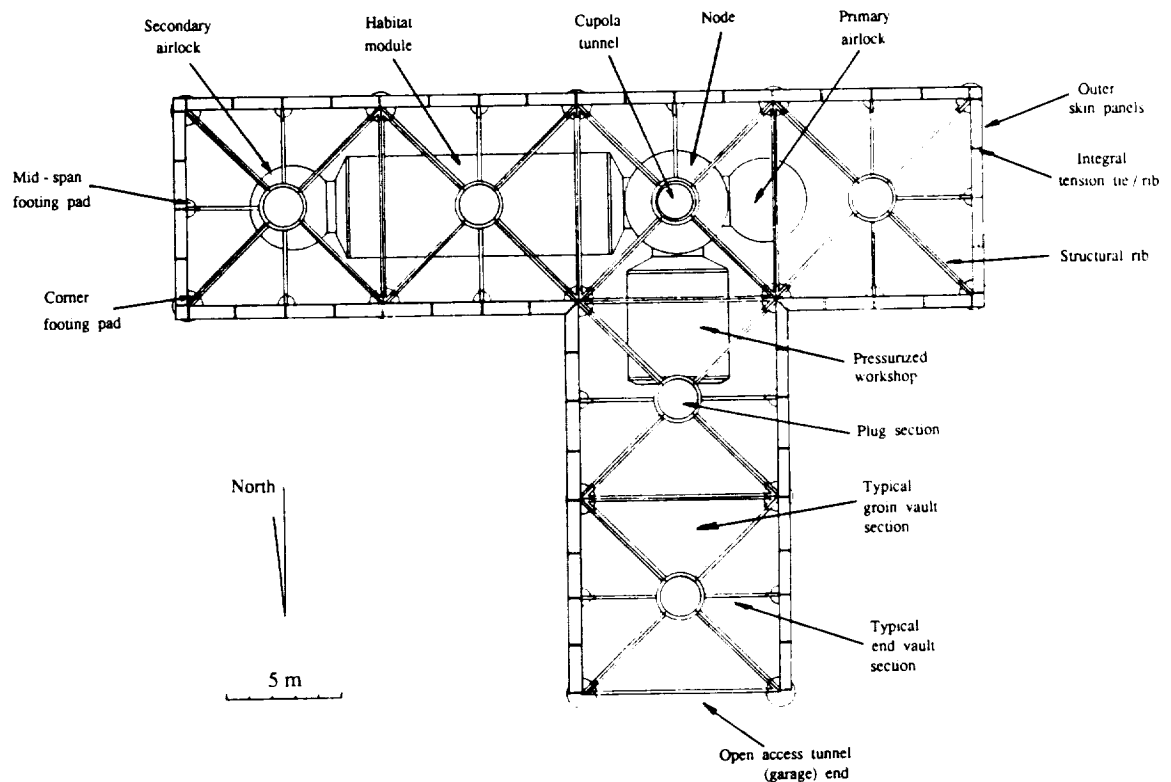
Figure 2-8 The initial habitat system consists of SSF-derived pressurized modules.
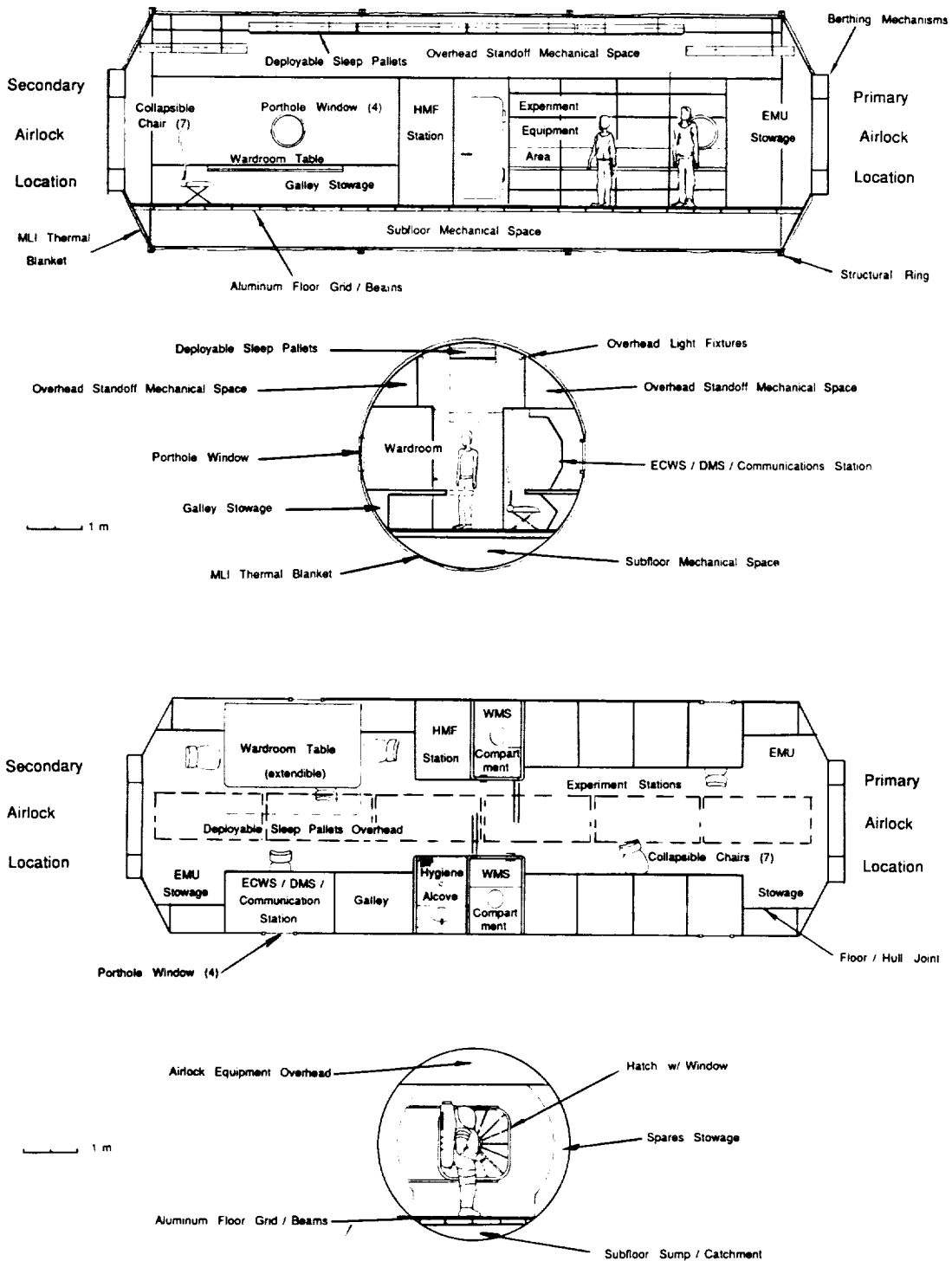
Figure 2-9 *Habitat / laboratory module accommodations are simple, optimized for intermittent human onsite activity.*

Some presumed details are embedded in our reference crew system concept. First, removing excessive EVA dust must be accomplished by a "dustlock" feature of the airlocks. This might be a shower using recycled and filtered water, although uncertainties about the wettability of dessicated lunar dust may argue for a gas-jet system or electrostatic precipitators. Many schemes have been proposed for dust control on EMUs (spacesuits); the best (simple, lightweight and thorough) remains to be determined. Deposits of clumped regolith would be brushed off prior to entering the dustlock. Second, the cupola tunnel protrudes through the regolith shield over the connecting node, thereby introducing a streaming path for radiation into the habitat system. Both direct viewing by shirtsleeve crew and complete "storm-sheltering" are essential, albeit competing, requirements. A simple solution would be an internal shutter plug of polyethylene in the cupola tunnel, which could be closed when the cupola is not in use, and during SPEs.

The heavy and bulky habitat system arrives in two pre-integrated packages on separate flights (node, cupola, primary airlock and workshop first; then hab module and secondary airlock). These two units are emplaced and connected robotically. SSF hardware is designed for assembly in orbit, so its docking adapters can perform that same function on the Moon if they are brought together in a slow and controlled manner. The connection task is then reduced to one of unwrapping, inspection, possible cleaning, final positioning and verification. Since the pressurized system is heavy (about 30 t total), a large bearing area is indicated for foundation. Although for simplicity we show the modules resting directly on their prepared gravel bed, thermal considerations (avoiding cold spots on the hull) would probably dictate that a low-conductance cradle, or trunnion-mounted struts, be used.

For reasons of safety, expandability and maintainability detailed in section 1.6, the regolith-based radiation shelter is a separate structure erected over the emplaced modules. Figure 2-10 shows two early design approaches to configuring a modular, 0.5 m thick cavity wall around a pressurized habitat system. Figure 2-11 shows the reference scheme, a groin-vaulted tunnel. The sections are erected, fastened, completed and filled with regolith robotically. If unconsolidated regolith averages 1.5 t/m3 in bulk density and is emplaced without macroscopic voids, a 0.5 m layer should limit the total dose to blood forming organs (BFO) to less than 20 rem/yr. This includes a continuous GCR flux, as well as one extremely large (8/72 class) SPE per year (exceedingly pessimistic). The current astronaut limit is of order 50 rem/yr. Void-free filling probably requires vibration and weight (tamping), as lunar regolith clumps together like damp beach sand. The

Radiation trap entrance alcove

Rooftop radiator assembly
Hinged, folds flat for transport
Rig tension cables to deploy

Roof - panel regolith trays
Corrugated panel spans beams
Sides hinge down for packing
Joints keyed to prevent radiation streaming
3 sizes (x 24, x 8, x 1)
Section - removable

Roof beam
Structural column
Cross brace
Wide - flange sections, high - strength Al
Robotically welded frame structure

Modular regolith cavity wall
Hinged, folds down for transport
Shelf angle optimized for regolith repose angle
Keyed side panels prevent radiation streaming
Tied to columns, bear on continuous footing
Section - removable separately from roof

Continuous footing
Channel section, high - strength Al
Distributes building loads
Accommodates uneven conditions
Defines clear geometry and robotic working base

5 m

Simple structure system, little extraneous material,
few joints, no mechanisms

21 % lighter structure (6 mt), less and easier
regolith - moving than shed concept

Frame arches
High - strength aluminum I - section
Complete half - arch units
Site - welded at footing and ridge

Brace / separators
Fold out from each arch, weld to next

Corrugated double skin
Lapped corrugated panels riveted to frame
Cavity filled in layers as wall is built up
Outer skin stops at regolith repose angle of 35°

Regolith fill
Vibrationally settled to 1.4 g / cm3
Adjacent segments can be filled and emptied
individually to facilitate lateral expansion

Freestanding end wall
Self - supporting, tied to vault ends, lap - corner joint
Separately removable to facilitate longitudinal
expansion

Continuous footing

5 m

1 m

Figure 2-10 A variety of regolith-based radiation-sheltering schemes were investigated.

32

-- 0.5 m regolith (average density = 1.5 mt/m3) yields 7 rem max SPE dose,
    13 rem/yr GCR dose (50 rem/yr astronaut allowable)
-- Straddler holds 0.3 m regolith sandwich panel over open tunnel entrance for SPE
-- Inner vault sections transported nested
-- Foundation pads positioned & cabled together, then gravel layer deposited
-- Construction starts from tunnel intersection around cupola, inner structure built first
-- Outer skin panels attached from bottom up, cavity filled with regolith as built
-- External connections for power supply, thermal rejection, communications
-- 3 ganged 1 x 15 m rooftop radiator modules with post-tensioned sunshade
-- 14 mt total shelter hardware mass
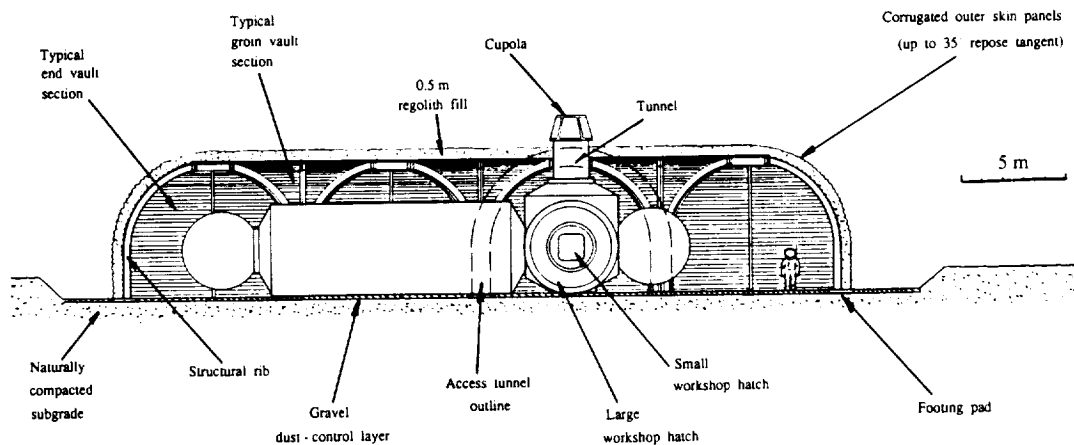
Figure 2-11 The reference sheltering scheme is a simple system of vault sections, with an outer skin of corrugated panels.

continual GCR bombardment should allow detecting voids within the sheath simply, by means of a radiation counter, to verify proper filling. Figure 2-12 shows that the main access tunnel is left open at the end. This facilitates simple, axial vehicular access to the workshop module for delivery both of components requiring IVA maintenance and of logistics resupply modules. The tunnel opening, exposed to GCR, represents just a small fraction of the overhead hemisphere. For SPE protection, a dedicated regolith-sandwich panel (not shown) would be hoisted in front of the opening by one of the straddlers.

The mass of the filled cavity structure is quite large (of order 1000 t), and so requires careful attention to foundation. The weight of the structure's plan projection can be thought of as being carried to the ground by the ribs (the vertical portions of the walls bear on the ground directly below them). Foundation plates are sized such that, if resting on undisturbed regolith 1 m below grade, they will not settle more than 2 cm under full load. Plates at the bay corners are thus larger, since they accept load from more ribs than do the mid-span plates. After grading, these plates are laid out, and connected with cable tension ties across the ground plan. Then a layer of dust-control gravel 5 cm deep is
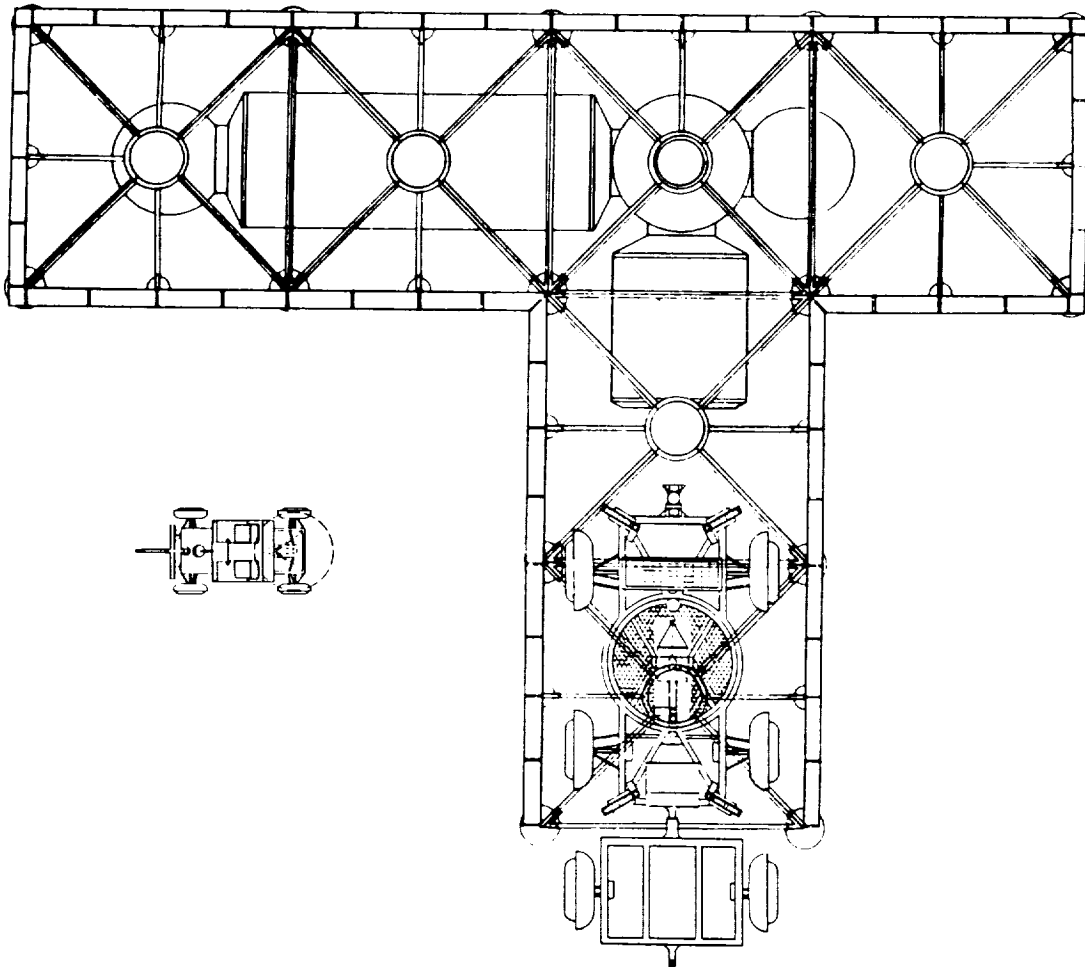
Truck entering garage

Figure 2-12 The rovers and trucks can enter the shielded, unpressurized "garage".

deposited and compacted over the ties, leaving only the foundation plates exposed. The superstructure is erected on and riveted to these plates. The structural bay is dimensioned to coincide with an eventual network of full-size SSF modules connected by vertically oriented SSF nodes.

The groin-vaulted system has an inner skin comprised of just three types of parts. These are an end section (used to form side and end walls), a joint section (used to connect bays and form tunnel intersections), and a circular plug (used to close the vault apexes wherever a cupola tunnel or a utility feed-through does not protrude). The two section types are of corrugated aluminum, with inner stiffening ribs at the edges and center. The

edge ribs of adjacent vault sections are riveted together as the structure is erected. Sections are transported nested, and positioned by the straddler. Construction begins at the node and works outward along the tunnels. The outer skin is built up in courses from the bottom, and consists of sheets of corrugated aluminum. They are riveted, overlapping, to 0.5 m tension ties which stud the outer face of the inner skin; each course is filled with regolith before the next course is attached. No outer skin is required above the point where the vault tangent equals the angle of repose of unconsolidated lunar regolith (35°). Thermal radiators and communications equipment are deployed on top.

Expanding the shelter requires only removing a few wall sections to install additional tunnel. The job of grading, graveling, positioning modules, and erecting and completing shelter sections is inarguably more difficult once the first-generation habitat system is finished, primarily because some vehicular access and maneuvering room have been lost. Nonetheless, a prefabricated, modular system requiring only assembly of a few parts seems to be the most reliable and believable approach for an initial base.

POWER PLANT - Power production is a utility function; however, for a lunar base the equipment required is without question a primary element. Photovoltaic (PV) solar arrays are used for two purposes in our reference: providing power online during the lunar day, and charging storage systems for use during lunar nights. Figure 2-13 shows an early concept for a tracking solar array, based closely on available space array blanket technology. Developed before our robot concepts took shape, it would have required complex assembly operations on the lunar surface to deploy. Figure 2-14 shows the iterated reference power plant: a freestanding, tracking 20 kWe unit. The panel structure is an 8 x 14 m rigid waffle panel of plated Gr/Ep. GaAs-on-Ge cells allow at least 15.1 % EOL efficiency at a nominal operating temperature of 150° C. (Recent advances in high-efficiency layered cell technology indicate that substantially more output than 20 kWe may be possible from an array of this same size.) Each whole unit masses 1.25 t.

No assembly is required; designed to be transported intact, the unit requires only deployment, and connection to a utility bus. The plate folds for transport, protecting the active surface. Hoisted by a straddler into position, the unit is deployed by the straddler's manipulators. The panel unfolds, its tripod-legs are telescoped out and locked open, and

Supporting struts

End - mounted tracking motor
Sized redundantly
for 6 ganged units

Sized for the energy needs
of one 6 - crew habitat module

20 kWe daytime load, plus
40 kWe electrolyzer storage load

Blanket support frame
Interlock to gang units

Fixed axle

1 m auger anchor pins

6 array blankets	850 kg
Blanket support frames	1500 kg
Tracking motors & axle	200 kg
Cabling and fittings	200 kg
Base & foundation structure	550 kg
Mass growth	495 kg

3.8 mt

5 m

Photovoltaic Cells

5 x 5 cm GaAs on Ge substrate cells
Fused silica covers
18 % nominal EOL efficiency
110 C operating temperature
15.1 % overall conversion efficiency

Hinge - stiffener

Flexible Blanket

Multilayer kapton / copper / adhesive flexible blanket
Molybdenum hinge - stiffener joints are joists
   spanning blanket width
Blanket / hinge lines withstand at least 60 N / m post - tension
85 % cell packing efficiency including hinges
Edge - mounted wire harnesses
Harness - fold bearing pads treated with MoS2
   solid lubricant

Wire harness

Fixed axle

Passive pivot

Support Frame

Erectable - frame I - beams receive joist loads for
   longitudinal stiffness, react post - tension force
Hinge - stiffeners deploy within channels, on beam flanges
Deployment drive pinion racks along beam web
Support frames lock together for ganged modules

Node fitting

Support struts
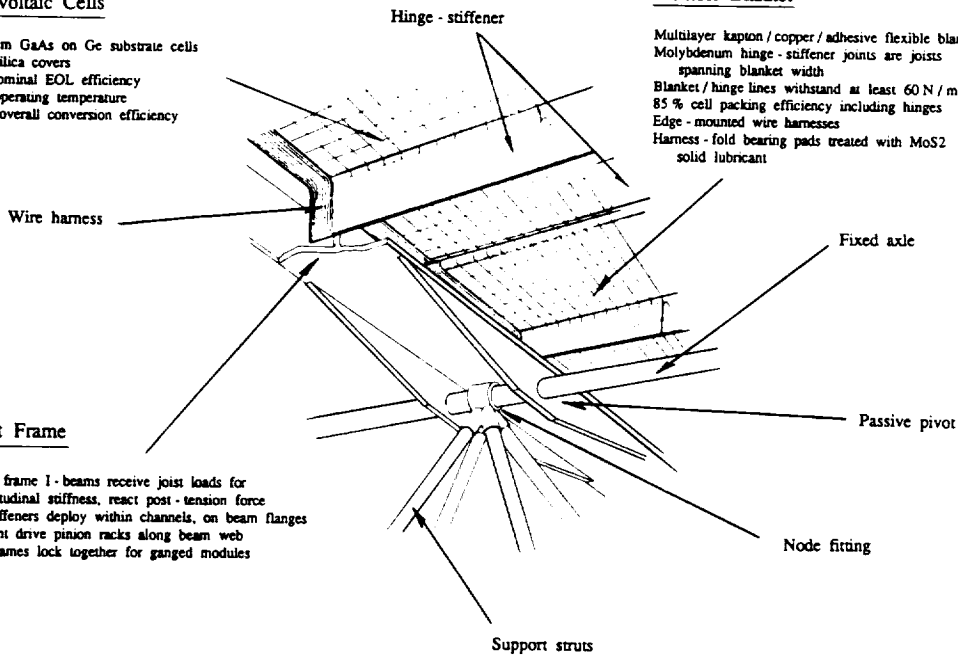
Figure 2-13 An early solar array concept proved complex to assemble onsite.

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auger pins are screwed down into consolidated regolith to anchor it in place. Two redundant motors keep the rigid array normal to the sun line during the lunar day. The motors and controller are maintained, and the array surfaces cleaned when necessary, robotically. An electrostatic precipitator appears to be a good option for dust removal. As the figure shows, the active surface is sufficiently high above ground level that crew activity is expected to cause little dust problem; to limit the vehicular contribution, we require the access roads around the arrays to be paved. Reducing and intercepting landing pad debris at the spaceport compensates for the final, major dust source. (Landings can occur at virtually any time once landing beacons are emplaced; during lunar afternoons the active surfaces of all arrays will be facing away from the spaceport dust source, for example.) This combination of measures fit well with our operational philosophy for the base, and did not require any additional weight and mechanism for array covers.
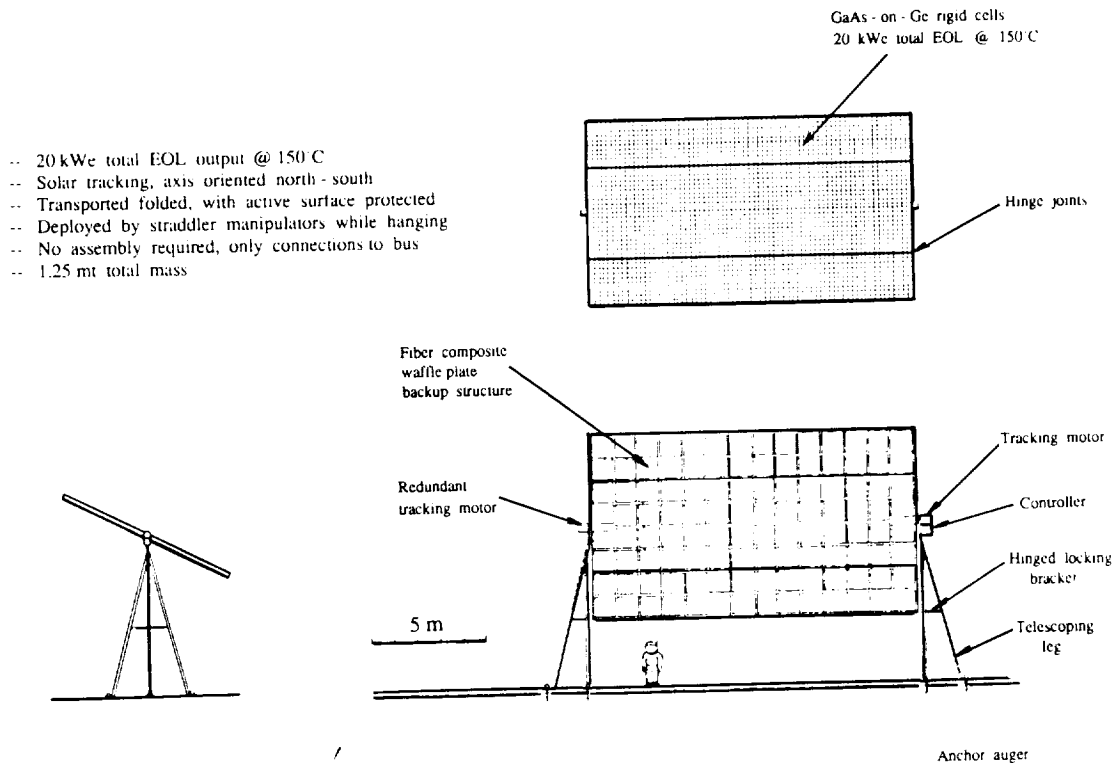
Figure 2-14 The reference photovoltaic unit is deployable without assembly.

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Our nighttime power plant consists of regenerable fuel cell modules (RFCs), shown in Figure 2-15. RFC technology is well-understood, and is the non-nuclear method of choice for deep-space mission concepts subject to intermittent solar flux. Each generates 20 kWe for the 336 hr duration of the lunar night. It combines hydrogen and oxygen, producing power and water. The water is stored, and electrolyzed during the day (with power from the PV units) back into the original reactants. No consumables are needed, but the overall efficiency is conservatively only about 50 %, so charging it requires 40 kWe. Excess heat (the lost 20 kW) is radiated to space. Packaged as shown, it fits STS payload bay dimensions. The reference design masses 25.4 t; this could be reduced a little by designing a more efficient structure, and possibly through liquefying the reactants for cryogenic storage (resulting in smaller, lighter tanks), although this would introduce additional operational complexity and the weight of the refrigeration equipment. The roughly 1 t/kWe-output specific mass is inescapable for a system which lasts throughout the lunar night. The straddler is required to emplace or reposition the device, which requires no assembly on the Moon.

Our scenario requires 24 of the modular PV units, and two RFC modules. One PV unit provides daytime power to the habitat system (for ECLSS, operations and laboratory equipment), and two more charge a dedicated RFC module for that same purpose at night. This insures a nominally steady supply for the inhabited systems. The oxygen industry (reactors, liquefaction and refrigeration) requires 18 PV units for direct daytime use, plus two to charge an RFC module (used for equipment keep-alive power, LLOX refrigeration, reactor cool-down bed fluidization, and hydrogen compression at night). One additional PV unit is provided initially, for charging mobile robots, for margin, and for redundancy.

The units must track the sun, which for an equatorial base means their pivot axes must run north-south, parallel to the ground. And no array may obstruct another's view of the sun from dawn to dusk. This leads most simply to the linear, north-south installation which appears clearly in Figure 2-3. All of our power utilization calculations are based on a 300 hr lunar day, which is about 90 % of the full lunar day. This discounts the sun when it is nominally within 9° of either horizon, a conservative assumption intended to account for undulating terrain and operational margins. Given the dimensions of our PV

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H2 tanks	7
O2 tanks	3.5
Reactants	4.2
Water tanks	0.5
Pump packs	0.3
Electrolyzers	0.3
Fuel Cells	0.3
Plumbing	0.3
Control Electronics	0.1
Power Processing	0.3
Cabling	0.1
TCS	1
Pallet	4
Mass growth	3.5
	25.4 mt

40 kWe input to electrolyzers   20 kWe output from fuel cells
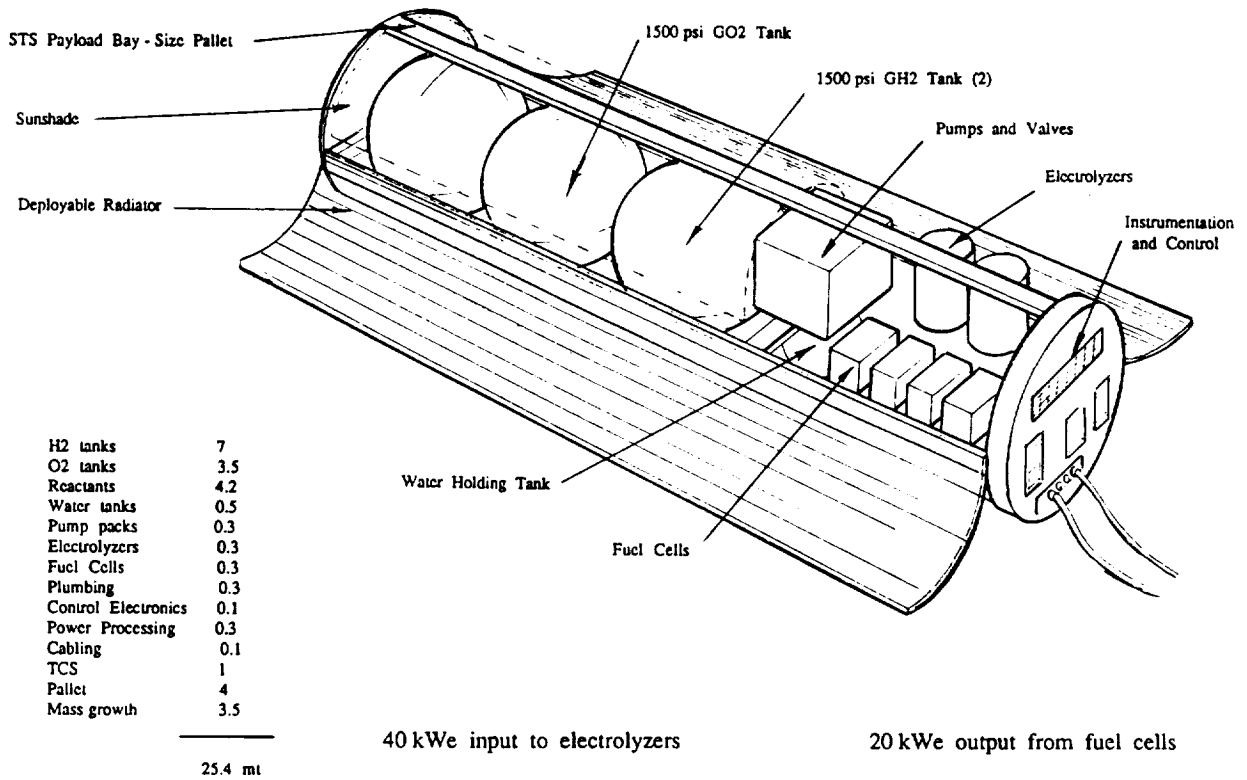
Figure 2-15 Regenerable fuel cells store power for use during the 2-wk lunar nights.

units, an alternative array configuration would be to base them along the sun's track, on 55 m centers in flat terrain. This would incur no additional view penalty. Indeed, several parallel north-south lines would be the proper choice for a solar field a few times larger than ours, because it would minimize both DC transmission losses and driving time out to the remote arrays. For our two dozen units, however, the site plan as shown minimizes the amount of site preparation required. The construction sequence would be to grade the north-south power plant strip, gravel and compact parallel access roads flanking an unpaved strip up the middle, deploy the power plant bus in that center strip, and then set up the PV units in the central strip, over the bus cable, and connect them to it.

OXYGEN PRODUCTION - The industrial plant consists of three oxygen-producing, fluid-bed reactors (Figure 2-16), and one oxygen storage depot for each landing pad developed. Operating one batch per lunar day, the reactors reduce lunar ilmenite ($FeTiO_3$) with high-temperature hydrogen gas, producing water vapor which is then electrolyzed.

Together the plants consume 360 kWe and 160 t of feedstock per lunar cycle, producing a total 8.3 t LLOX in that time. The plants must be emplaced, connected, filled, run, emptied, and maintained robotically. Simplicity was given higher priority than strict efficiency. We concluded that the greater requirements for power and mass-throughput required by a less efficient design would be more achievable and more reasonable in an early scenario than would a complicated --- but still reliable --- type of process plant.

The pressure vessel is of carbon/carbon (C/C) composite, with a vapor-deposited alumina abrasion liner on the inside and flexible ceramic insulation (TABI) on the outside. Each batch reactor consumes about 130 kWe while heating up, and about 115 kWe while running during the lunar day (the insulation is sized to lose 110 kWe steady-state). A straddler charges each vessel with two hoppersful of 55 % ilmenite-enriched feed (53.2 t) at sunrise. The vessel is then sealed and pressurized to 10 atm with hydrogen. A pump circulates the gas through a plenum at the bottom of the vessel, to bubble up through the bed of fines and fluidize it. This increases the reaction surface area. Heating the flowing gas in turn heats the solids to 900° C over 150 hr, half the lunar day. As the reactor runs, the gas (90 % H_2, 10% H_2O reaction product) removed near the top of the vessel is stripped of 96 % of its suspended dust by two staged cyclone-separators, before passing by the zirconia membranes of a gas-phase electrolyzer. The electrolyzer pulls oxygen atoms away from any oxygen-bearing molecules in the gas flow, including the water vapor. The hydrogen remains in the circuit to enter the reactor again. The pure oxygen gas is piped away as the plant runs at temperature for another 150 hr. Keeping the spent solids fluidized as they cool down into the lunar night keeps them from caking (the circulation pump takes comparatively little power). Then the hydrogen is compressed into storage bottles (this also takes little power if done slowly during the lunar night), and the evacuated reactor is finally opened and tipped before dawn. With cleaning assistance from a specialized end effector on one of the trucks, the spent solids are emptied into hoppers positioned by a cart on the rails below, to be removed to a deposition site by a straddler. After inspection, the reactor is ready to be filled again.

This reactor concept design was developed to provide reference details for consideration of robotic operations. Many questions remain unanswered about the best ways to extract oxygen from lunar feedstocks. A wide variety of processes has been proposed, but none are yet verified to work well under native lunar conditions. Other reactions than ilmenite reduction (carbothermal reduction, for example) may require less

TABI insulation (7 cm)
Circulation pump
C / C Pressure vessel (6 cm)
Alumina liner (2 mm)
Feed / empty / clean hatch
Rack and pinion drive
Static solids level
Gimbal stand
Hopper cart rails
2 staged cyclone separators
H2 / H2O line
GO2 line
Zirconia electrolyzer
Evacuation compressor
H2 bottle
Distribution plenum
27 mt capacity hopper
Naturally compacted regolith

GO2 line
2 staged cyclone separators
Hopper below
H2 storage bottles
Cart rails
Gimbal stand
Footing
Rack
Pinion drive
5 m

-- Fluid - bed batch reactor, process at 10 atm, 900° C
-- 53.2 mt, 55 % enriched ilmenite regolith charge (< 2 mm)
-- 133 kWe heat - up power
-- 150 hr heat - up, 150 hr process run
-- Gas composition nominally 90 % hydrogen, 10 % steam
-- 30 mt total mass, landed intact

Figure 2-16 Fluid-bed batch reactors reduce ilmenite with hydrogen to yield oxygen.

beneficiation or yield better synergy for lunar bases. In addition, fluid-bed reactors are extremely challenging to design successfully, being reportedly the most complex and obstinate type of process plant yet invented. Major concerns are: absolute size and aspect ratio appropriate for lunar gravity, reliability problems due to thermal and pressure cycling if operated in batch mode, lock-hopper reliability if operated in continuous mode, and the possible need for a pre-oxidation reactor to evert ilmenite-containing grains and remove sulfur. Although it is far beyond the scope of this operations study to develop a well-traded reactor design, our concept was iterated in response to these issues. The C/C pressure vessel was chosen for light weight and good performance in a hot, reducing environment. Joining and sealing the composite material with metal fittings is an issue, but appears tractable. And our vessel shape was chosen according to advice from specialists in fluid-bed reactor design. Cyclone separators were chosen because they have no moving parts, and zirconia electrolyzers were selected because of their simple design, modularity, tolerance of contaminants and purity of product.

The industrial facility installation occurs in stages, spread over many lunar cycles and cargo delivery flights. Schedule details are contained in section 3.1. A 1 m deep conduit trench is excavated, connecting the reactor field site with the oxygen storage depot

site. The reactor field is leveled 1 m deep as well. The oxygen gas line is unrolled into the trench and covered, and the traffic area around the reactor field is graveled 5 cm deep. Deployable rails are set down on the exposed bed of undisturbed regolith in the center of the field and anchored in place; then the three reactors (each brought intact by one lander flight) are emplaced over the rails, and their power, data and oxygen lines connected up. Each reactor masses 30 t, and when filled exceeds 80 t. The reactor footing is sized to limit settling to less than 2 cm in the naturally compacted regolith found 1 m below original grade.

Oxygen gas generated in the reactors is collected into one line which runs underground, cooling passively, to the LLOX storage / liquefaction depot (Figure 2-17), which condenses and stores it cryogenically until needed to fill a lander's LOX tanks. A single depot, dedicated to one landing pad, stores enough LLOX in two tanks for two entire lander loads (half the initial annual production). The tanks and exposed lines are enclosed by debris bumpers filled with multi-layer insulation (MLI). Often it is assumed that cryogenic storage tanks on the Moon should be buried, since a stable environment at 57° C is available less than a meter below the surface. We considered that the operational complexities of installing and maintaining buried tanks exceeded the inconsequential up-front cost of additional MLI to allow the tanks to be exposed to the 1.4 kW/m^2 solar flux and daytime ambient 150° C temperature on the surface. Thus all the depot equipment is accessible for inspection and maintenance. The depot consumes 60 kWe to liquefy incoming oxygen during the second half of the lunar daytime (that power becomes available when the reactors' consumption drops for that steady-state period). Three refrigeration units are each capable of half the cooling load, allowing offline maintenance. The machinery and radiator are both stood off the ground 1 m to minimize casual dust contamination from local crew activity. (Apollo results show that less than of order 5 % of the dust kicked up by astronauts exceeds waist height.) The site on which the depot is assembled is graveled 5 cm deep (except for the tank footing area) after being cleared down 1 m. The tank footings are sized according to our standard 2 cm settling limit in undisturbed regolith at the 1 m locally excavated depth. Each storage tank, the pallet of liquefaction machinery, and the radiator modules arrive intact. Required assembly amounts to deploying the trussed platforms, emplacing the units, deploying the fixed radiator sunshade, and connecting power and fluid lines.

2 Al LLOX tanks
(each holds full lander capacity)
MLI, polished Al debris /sun shield

Liquid fill &
vapor return lines

5 ganged 1 x 15 m
radiator modules

Sunshade
overhang

-- Plant machinery emplaced intact
-- Fluid connections QD, above ground
-- Embedded controller & sensors
-- 8.3 mt plant mass
-- 15 mt fluid lines mass

Footing

Column

3 refrigerator units,
each 50 % total load nominal

Lines to
launch pad

Post - tensioned sunshade
(75 % space view factor)

Buried GO2 bus line
from oxygen reactor field

Telescoping
"tentpole"
structure

5 m

Gravel dust - control layer

Standoff platform

Footing

Radiator

MLI blanket

Standoff truss

1 m
excavated
depth

Buried liquid fill
& vapor return
lines to launch pad

Figure 2-17 A storage depot liquefies the oxygen, and pumps it to landers when needed.

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2.3 UTILITIES

For this study, we define utilities as elements which, while required, are clearly secondary in mass or complexity to the primary integrated systems. They provide services which connect, facilitate or enable the primary elements to function as required. Fundamental changes in these utility elements generally have only minor effects on the integrated base concept.

THERMAL REJECTION - Rejecting low-grade heat during the lunar daytime is a problem not adequately traded to date. Vertical radiator panels which face north and south are commonly shown, but do not work well for this temperature regime since they see so much of the hot lunar ground. Options include surfacing the ground with mirror materials to create virtual space views locally, tracking the radiators themselves to avoid sun-viewing, and using tracked or fixed sunshades. Although we did not complete a full analysis of the shadow, absorption and reradiation environment for such a device, we chose this latter, passive approach to limit both the radiator system size and complexity. Fixed, lightweight, post-tensioned sunshades treated with selective coatings are erected over all the radiators in the reference scenario. Mounted as shown, such a sunshade still permits a 75 % space view factor, yet keeps the radiator in its umbra for the middle third of the lunar day, and in its penumbra for 76 % of the day, throughout the lunar year. Although the solar incidence angle at the edge of the penumbra is only 21°, an almost horizon-to-horizon sunshade strip might in fact be required.

A strip-shade solution introduces high view-factor penalties for radiators with low lateral aspect ratios. Our reference radiator module is 1 x 15 m in plan, comprised of an armored pipe spine (connected in series with the cooling loop), to which are mounted many unarmored, parallel, self-contained, finned heat pipes. Heat is conducted through the pipe wall into each heat pipe, which then distributes it along 1 m of upward-looking radiator fin. This way, the weight penalty for meteoroid shielding is limited to a simple, main loop. System performance degrades gracefully with the functional loss of individual heat pipes (due to fluid loss to space after puncture, for example). A defective heat pipe assembly can be removed, and a replacement clamped around the loop pipe to restore nominal performance. The 1 x 15 m radiator modules can be ganged together. The widest configuration we baseline is 5 modules, preserving a plan aspect ratio of 5.

DEBRIS BARRIERS - Our three-tiered strategy to limit damage to vulnerable systems by exhaust plume debris has been outlined already. The first line in that defense is a set of lightweight, simply-deployed barriers which block direct trajectories for hazardous lofted particles. Our reference lander produces a maximum hovering thrust of 71.2 kN. Data from other published studies indicate that a barrier 10 m high, 50 m away from the blast center, is adequate to intercept virtually all of even the finest particles. Without an atmosphere to transport dust, a simple barrier which leans slightly in toward the source should prevent secondary effects. We assemble such a barrier only where needed, around that portion of the perimeter of each landing pad which faces the rest of the base. It is composed of separate units, each 14 m long, emplaced so they overlap in elevation. They are made of corrugated Gr/Ep sheet, with simple, lock-hinge legs. A straddler deploys each by positioning its bottom edge along the ground, then tipping the top over, unfolding and locking the supporting legs, and setting them down. Auger-anchors could be used as for the PV power units if required. However, since the barriers are extremely close to the lander touchdown point, we anticipate that unanchored or breakaway positioning would be safer for crash contingency.

HOPPERS - Our reference hoppers are simple, passive transport containers which are brought to the Moon nested. Each masses 1.2 t, and can hold 16 m^3 of material, or about 27 t (half an oxygen reactor charge, and close to the capacity of the straddlers). The hoppers have chutes built into the bottom, which can be opened by a robot manipulator, for emptying. They are transported in two ways: by a straddler, or on a wheeled cart which travels on the rails beneath the oxygen reactors.

STORAGE - Our reliability analysis (section 3.8) reveals the crucial need for spare parts to keep the base functioning smoothly. A reasonable system-level spares budget is 15 % of the mass of active components. This represents a substantial inventory, one which our base scenario accumulates, gradually as the base is built up. Although replacement mechanical parts must be packaged carefully for transport to the lunar surface in the first place, we anticipate the possible additional need for some type of storage shed. Albeit unpressurized, this could provide one more level of protection from debris and solar flux, and might facilitate inventory management. We do not show such a structure in the site plan because the need for it has not been conclusively demonstrated. However, fabricating

it from uncovered habitat-shelter sections would standardize design, manufacture and assembly, and permit direct, robotic truck access.

GUIDANCE BEACONS - Two kinds are required. One allows precise range and range-rate (6 DOF; or distance, altitude, azimuth, and heading) computation by landers descending from LLO. The other provides relative position data for mobile robots and their components around the base. Both are simple, self-contained units.

A landing beacon is essential for targeting the same landing point, obviously necessary for repeated landings at a fixed base. And during terminal descent, the beacon, augmented later by detailed, onboard approach-terrain models, increases the probability of successfully repeated "pinpoint" touchdowns. Such a capability is necessary for many reasons. First, the prepared surface of the landing pad is constrained by construction resources to be small. Second, in addition to being immediately adjacent to the rest of the base, the landing pad is serviced by paved access roads, and lander vehicle conditioning systems including a LLOX retanking utility. Ground-servicing the landers can be more efficient if they can be expected to touch down in the same spot virtually every time. The landers will certainly have the ability to hover, setting down like helicopters on Earth, but permanently installed ground-truth beacons are required to close the sensing loop tightly. Finally, the design of our debris barriers around the landing pad depends on their distance from the nominal touchdown point. To enable effective debris interception then, the touchdown geometry must be consistent. Most of these constraints obtain regardless of the specific base design. Compact, long-lived beacons powered by RTGs are envisioned for lander navigation. Their broadcast would be a simple, strong signal, which the GN&C equipment onboard the lander would process to calculate navigational information.

Local positioning and scene registration is required for the fleet of robots (and processor-assisted human-operated equipment) which will be moving around the base on the ground. The scale of this need ranges from navigating entire vehicles near the base, on its roads, and around its fixed elements, all the way down to controlling manipulators within the constraints of a local worksite. Proper functioning of a robust A & R system depends on an adequate machine model of the operating environment: geometry, properties, kinematics and kinetics (much of which can be available a priori). One means of machine registration is passive and self-contained, such as interpreting parts, markers and barcodes by video and range sensing. A second means is mechanical registration to

structures such as docking bays and grab points. A third, complementary method relies on active, implanted means such as electromagnetic (EM) beacons. Such devices could be small (walnut-sized), self-contained (battery-powered), and capable of operating for years before replacement. If incorporated into the design of fixed elements, fixed base features, manipulator arms and special attachments, EM beacons can enable antennas on mobile elements to relate beacon-centered coordinate systems computationally. Thus, the machine controllers can determine with millimeter accuracy the relative positions of all moving components as tasks are performed. Simple navigational paths would not require overlapping beacon fields, but critical areas and fine-scaled worksites would benefit from redundant positional sources.

COMMUNICATIONS - Again, two types are required: spacelink and local. The Nearside site allows continuous, direct transmission to Earth orbit. This link must have a high bit rate (of order a few hundred Mbps), to support the extensive Earth-based data analysis, task planning and execution supervision that we can expect an A & R lunar base scenario to require. A fixed, high-gain antenna with either duplicate or low-gain backup can serve the function. Since the onsite control center would be located within the habitat system, these Earthlink antennas would most simply and safely be mounted on top of the radiation shelter. A similar (but lower data rate and target-tracking) antenna system needs to be dedicated to space transportation vehicles in transit between Earth and Moon, in LLO, and on approach and launch trajectories. This system may also reasonably be habitat-mounted.

The successful performance of a hierarchical control architecture acting within a changing environment depends on maintaining communication links within and among all its levels. Local communication systems are required for the base controller to stay in touch with EVA crew, monitor elements' status, issue operations commands, and coordinate simultaneous activities. The base controller serves this coordination function in several modes: autonomously, together with local crew, and together with Earth-based controllers. Links are also required among elements (whether process plants, mobile robots, or crew) in the field, to insure smooth operations in constrained or joint worksites. Some fixed elements may be linked by permanent data lines, but the mobile elements require transceivers. The choice of RF or IR wavelengths was not traded in this study, because it has little effect on the integrated base concept. IR systems have the benefit of greater bandwidth, lower noise, smaller size and no crosstalk; however, their lenses would

require periodic attention to dust film removal. Both methods suffer from line-of-sight interruptions due to obstructions by base elements, or by topographical features (hills and the close horizon) in the case of near-base operations. Both methods could overcome this limitation, with some bandwidth penalty, by using orbital relays at L1, in HLO or LLO.

LANDER CONDITIONING & LLOX TERMINAL - Partially ground-basing the lunar landers introduces vehicle conditioning requirements more complex than those for the Apollo LM (which had none). Re-usable landers in an ongoing base scenario may eventually spend more time on the surface (where maintenance is at least potentially available) than in space; even in early phases, landers will sit dormant on the surface for times on the order of a lunar cycle. At the very least, dormant landers will require connection to a power source, so that their onboard thermal control systems can maintain a consistently nominal environment for the vehicle systems. Conditioning equipment will also include sensors to monitor various physical and chemical characteristics of the vehicle exterior, and perhaps additional, "plug-in" diagnostic equipment to complement the vehicle's own onboard status monitors.

The major lander servicing activity of interest in this study is LLOX loading. The terminal facility concept we baselined is essentially a valve box located at the edge of each central landing pad area. Such a device would be emplaced at the time the trench is dug for fluid lines connecting the terminal to its storage depot. Covered by an access plate mounted flush with the compacted, graveled surface of the landing pad, it would present no obstruction or hazard for the lander touchdown, yet minimize the length of umbilicals required. For the tanking operation, a truck with specialized attachments (described in section 2.5) would clean debris and dust off the cover, unseal and open it, and connect umbilicals to outlets mounted inside the subsurface box.

Landers will require other servicing best performed in space, especially at the beginning of an operations scenario. For example, the hypergolic attitude control system (ACS) propellants must come from Earth anyway, so should reasonably be tanked, along with the liquid hydrogen fuel also brought from Earth, in LLO. Inspections of those systems will however be performed at the surface base as well. Servicing done strictly in space is beyond the scope of this study.

FLUID LINES - Gas lines are required to collect the oxygen generated in the reactors, and conduct it to the LLOX depot. The gas is at 10 atm, starts out at 900° C and cools down to 150° C during its 70 m travel, buried 1 m underground. The main line is unrolled in a continuous length into a prepared trench and covered over. Connections at the line's ends are made above ground and left exposed for maintenance access.

Mixed-phase lines are needed to connect the LLOX depot with the LLOX terminal box. When beginning the fill, LOX will vaporize as it chills down the line and the lander tanks. A return line is thus required to complete the fluid loop back to the liquefaction depot. These will be double-walled lines to limit conduction and radiation heat leak, but require inside diameters of only a few centimeters.

POWER SUBSTATION - The two solar fields, and their storage units, require interconnection for redundancy (the habitat life-support functions get priority). Also, the industrial facility power demand varies greatly depending on the sun, the current phase of the oxygen operation, and taking units off-line, perhaps suddenly, during contingencies. We chose to collect these switching and regulation functions into a single, internally redundant unit, which could be landed intact, emplaced simply on the surface, and connected to sources, users and the base controller.

POWER, DATA & GROUNDING LINES - All fixed base elements require connection to the power utility. By power utility, we mean the two solar array fields, the two RFC modules, and the power substation which manages load-allocation among those four sources and the various user elements. Additionally, we expect that a common "chassis ground" for all elements would be advisable. In a dessicated environment, the friction involved in moving large amounts of fine particulates is a prescription for differential static charging, Although the lack of an atmosphere precludes conventionally hazardous spark discharges, equilibration and neutralization would probably be required to protect electronic equipment. Grounding cables could be easily accommodated along with the power lines. Any data exchange requiring permanent lines between fixed base elements could be accommodated the same way.

2.4   SITEWORK INFRASTRUCTURE

Even for a lunar base built of elements brought finished from Earth, conditioning and manipulating the native environment is required. Such preparation is generally called "infrastructure" by civil engineers. In the aerospace community, infrastructure typically connotes other meanings, so for clarity we use the appellation "siteworks" for base "elements" made by altering the site's natural properties.

FOUNDATIONS - Foundations on the Moon appear to pose a simpler problem than on Earth, for four reasons. First, moonquakes are very weak; founding to bedrock is unnecessary. Second, the complications of interstitial or adsorbed water are absent entirely in lunar soil. Third, the eons of fragmentation, pulverization, mixing and vibrational settling which generated lunar regolith have made it a highly homogeneous, well-comminuted substrate. Although our engineering knowledge of lunar regolith is incomplete, we expect that the principles which do develop will be widely applicable across the planet, and that regolith behavior will be generally quite predictable. Fourth, the relative density (fraction of bulk volume which is actually solid material) of lunar regolith is extremely high, again because of the vibrational effect of impacting meteoroids over geologic time. Within the first meter of depth, the relative density can reach values over 90 % (70 % is the practical limit for Earth soils which have been specially compacted). Indeed it is believed that lunar regolith, once disturbed, can never be recompacted to as high a relative density. While this natural packing complicates digging (treated in section 2.5), it is innately advantageous for foundations.

Some of our base elements are particularly heavy: the completed habitat radiation shelter, the full oxygen reactors, and the full LLOX depot. To maintain structural and functional integrity, settling is undesirable for these installations. For the purpose of this study, we designed a foundation scheme based directly on lunar regolith engineering data available in the Lunar Sourcebook. Our designs specify footings sufficiently wide to limit settling to 2 cm in undisturbed regolith at a native depth of 1 m. The excavation process we propose (in section 2.5) is capable of removing overburden carefully, leaving a flat, essentially undisturbed, freshly exposed ground surface at the 1 m depth. Metal footing pads are then placed directly on this surface.

Some cables, like those comprising the power bus to which each PV unit is individually connected, are most simply emplaced directly on the surface (in this case, on the leveled strip where the array units will be mounted) because they are out of the way. Others, like those feeding the oxygen reactors, the LLOX depot, and the habitat system, would present operational complications and risks if deployed on the surface. One option would be cable covers over which vehicles could drive, but we chose to deploy these cables more securely in 1 m deep trenches, dug with the bucket-wheel trencher attachment for the trucks (described in section 2.5). The task of digging the trench, unrolling the cables into it, and pushing the regolith back over, is extremely simple and quick compared to other activities in the scenario. Only continuous lengths would be buried; all connectors would be located above ground for maintenance access.

SENSOR HEADS - Tripod-mounts, possibly with masts for improving visible range, line-of-sight perspectives and effects of machine-machine occlusion, will be required as quickly deployable, reconfigurable sensor platforms around the base. Video cameras, laser scanners, laser alignment devices, EM beacons, debris counters and radiometers are among the device types anticipated to require temporary positioning.

LIGHTS - Earth is always visible from Nearside lunar sites. The full Earth seen from the Moon is about 80 times brighter than the full Moon seen from Earth. Nonetheless, task lighting is required to control illumination levels and angles for all times during the lunar cycle. Mobile robots have their own chassis-mounted lights, needed for crews and video coverage (robot navigation and manipulation systems using lasers and EM signals are indifferent to ambient light). Wall-mounted lights are required primarily to illuminate the inside of the radiation shelter around the habitat system. Similar units can be tripod-mounted if stand-alone local lights are needed.

CONNECTING ROADS - Wheeled vehicles are the most efficient means of general-purpose surface travel for the anticipated terrain of a lunar site. Wheels operate most efficiently on a prepared surface, because they expend too much power "climbing" as they deform and roll on soft or uneven terrain. Also, repeated traffic could be expected to churn up lunar regolith, destroying its native bulk structure and making it less trafficable. Finally, a prepared surface can mitigate dust generation during travel. For all these reasons, prepared roads would seem essential.

Several schemes have been published for lunar road-building. Arranged in order of increasing sophistication, they include: simple grading, graveling, paving with modular blocks, and paving continuously. Proposed material processes include compacting, sintering or casting; and energy sources include mechanical, microwave, focused solar and direct nuclear-thermal. Some schemes appear to show promise for integrated lunar manufacturing scenarios. In particular, the dielectric properties of regolith may favor microwave sintering, either of paving blocks or continuous roadbeds.

For the very earliest base, however, it is unlikely that something so fundamental as road construction will hinge on an experimental technology. Rather, one important purpose of an early base is to experiment with such approaches (not depend on them), developing them for more advanced application later. We chose a simple scheme: grading, graveling, compacting. This requires no equipment not already required for other construction and mining activities, and results in roads quite satisfactory for an early lunar industrial base. The gravel and sand needed are produced anyway as a result of beneficiating regolith into ilmenite feedstock; by the time the base roads and foundations are completed, a 2 yr reserve stockpile of reactor-ready ilmenite feed has been generated. For simplicity, we call this graveling method "paving".

Roads around the reference base are between 10 m and 30 m wide, depending on their expected traffic. The first roadbuilding task is to excavate a swath 20 cm deep, as wide as the road will be. An average of five straddler passes are needed to attain this depth for each 30 cm-wide strip excavated (one for initial leveling and four to remove the material). This may seem like a lot of excavation just to lay a road, but the 20 cm depth reaches material with a relative density of around 80 % in intercrater areas, and removes all craters up to about 1.12 m in diameter. The material removed is separated into stones, gravel, sand, ilmenite feed and gangue as it is being excavated, with these materials stored separately elsewhere. When the roadbed is completed, relatively dust-free gravel

and sand are deposited from hoppers carried by a straddler and spread as needed by a truck's dozer blade into a 5 cm deep layer. Simultaneously, a vibrating compaction roller towed by that same truck densifies the road surface. Terrestrial mining and quarry roads built in this manner typically have thicker gravel layers. The gravel component of beneficiated regolith is, however, a valuable material. Lunar base roads need not be designed for the continuous, heavy traffic withstood by conventional construction roads in Earth gravity. And using much more gravel than we propose would let roadbuilding alone dominate the equipment design and schedules. Our reference scenario has instead been iterated to balance quantitative requirements for base buildup with those for nominal oxygen production.

OPEN WORKYARD - The six mobile robots (2 rovers, 2 trucks, 2 straddlers) have a variety of attachments to specialize them for various tasks. Changing out attachments, storing the ones not currently in use, and performing planned maintenance on the mobile elements are activities all facilitated by having a dust-controlled workyard in which to perform them. A traffic node is also required to link efficiently the special-purpose roads extending out to the power field, the reactor field and the spaceport. Our centrally located workyard serves both needs, thus avoiding excessive paving. The reactor field maneuvering-zone and the dust-controlled area around the habitat shelter are both integrated into this open workyard as well, to simplify the overall paving geometry. The workyard is constructed just like the roads, except that the reactor and habitat substrates are excavated to the full 1 m footing depth.

SPACEPORT - Dust control is paramount for the spaceport, because the debris produced by just one landing exceeds by orders of magnitude, in amount and severity, that produced by locomotion and crew activity over long times. Leveling is not as immediately critical (after all, at least the first lander arrives and is unloaded on an unprepared site), but performing nominal spaceport functions on predictable, even surfaces decreases both the operational risk of accident, and fatigue-loading of the equipment. The spaceport facility concept we developed is both closely integrated with the rest of the site plan, and laid out in anticipation of further growth.

Since the touchdown of a hovering lander is in many ways analogous to the touchdown of a helicopter, we have adopted an analogous design strategy. The

maneuvering area available for setting down the lander is circular, 100 m in diameter, and cleared down to 20 cm depth like the roads. The actual landing pad is a concentric area 70 m in diameter, paved with compacted gravel. (The lander jet will loft gravel less than sand and dust. However, it may turn out that gravel paving is still too erodable, particularly if individual landers are used many times. Fashioning stable paving blocks of native material may prove to be an industry with high early payoff.) This pad is contiguous with the straddler access road (used for offloading the lander) and the diametrically-located LLOX depot servicing road, which simplifies road-building. The debris barriers are erected, staggered as described earlier, around the base-facing perimeter of the 100 m spot, so that the LLOX depot is protected as well. Restricting straddler access to the east as shown seems, at first glance, to require excessive roadbuilding. However, one of the first growth activities of the initial base would be to enlarge the spaceport. Because landers approach from the east, and because the debris hazard from landers obtains for other, grounded landers as well, we plan spaceport extension to the north and south. The spaceport access road thus connects the base core to two, parallel north-south roads: one for access to each of several future pads, and one for service access to the separate LLOX depots serving them. After debris barriers enclose enough of the pad perimeters to keep them from seeing each other's debris, only eastern access is left to the straddlers. The spaceport thus ends up being the border between the lunar wilderness over which the landers approach, and the growing base beyond. Proximity is maintained, and necessary roadbuilding is minimized and efficient.

DEPOSITION SITES - There are two kinds: one for waste disposal and one for depositing excess material generated by construction or industry. As already discussed, spare equipment will arrive packaged and protected. Broken equipment will be repaired as possible to await further service life. Equipment broken beyond the ability of the base to repair represents an extremely valuable source of parts and refined materials for other, unanticipated purposes. Thus it needs to be stockpiled, and the storage shed already mentioned could provide an appropriate place. Supplies for the crew (consisting mostly of organic materials) will arrive packaged in logistics modules. In our scenario, such modules are temporarily attached by a truck to the small hatch in the exposed end of the workshop module. The crew performs a shirtsleeve transfer of supplies from the new module into the habitat system for storage and use, and packs their trash and stabilized waste into the new module. The truck then removes the logistics module to a deposition site. The light elements bound up in the trash represent one of the most valuable commodities on the

Moon, and need to be stored until more advanced industrial processes enable recovery for recycled uses. It is difficult to imagine a justification for "throwing away" anything taken to the Moon; and even more clearly than on Earth, "discarding" is a misnomer.

Excavation and processing of native lunar material poses a different problem. The amounts of unusable material are greater, and the investment in their generation is generally less burdened than for organics or defunct equipment. However, in most cases some value has been added by virtue of processing, and the material is being moved anyway. Therefore, deposition should, if possible, contribute to some other function, and should at least permit later recovery. The most evident example is the gravel and sand generated by beneficiating lunar regolith. Albeit waste from the standpoint of oxygen production, these are the most valuable materials generated during base buildup, because they are needed for paving. They are stored temporarily in roadside hoppers, which trivializes their "recovery" for use in paving. After base buildup, the enriched ilmenite feedstock would be stored the same way, for ready use in oxygen reactors. That feedstock generated during buildup would be deposited in a moderately recoverable manner (in a pile separate from other deposited piles), to be used as a reserve. The spent oxygen-reactor solids (primarily elemental iron and rutile) may be particularly useful as a sintering material, or as a "found" alloy for hot isostatic pressing (HIP); almost 2000 t are produced each year. The stones separated from excavated regolith would be deposited separately also.

75 % of excavated, beneficiated material, though, is gangue. It is now deficient in native iron, ilmenite and any other paramagnetic minerals the regolith contained originally, but it may be quite valuable for other material processes (for example, sintering building blocks, or producing glass fibers, or casting rock slabs). It is finely sifted, containing no particles larger than 0.5 mm in size. Well over half of it is finer than the human eye can resolve (less than 70 μm), and so is practically dust. Our scenario does have one critical use for such homogeneous material: filling the radiation shelter cavity-wall. However, that task requires only of order 850 t, less than the amount generated in only one lunar cycle. The rest needs to be put somewhere close (to minimize transport time), recoverable, possibly useful, but definitely out of the way. We left a north-south strip, 70 m wide, between the western edge of the spaceport and the eastern edge of the rest of the base, for this purpose. The gangue could be deposited in a shield wall between the growing spaceport and the growing base, leaving a gap for the spaceport access road. The straddlers would build such a sitework imperceptibly, by successive deposition passes. Given a 10 m height for the middle 40 m of width, 35° (repose angle) embankments

down to ground level on both sides, and 100 t/yr LLOX production rates, the shield wall would grow by 15 m in length each year the base operated, unless tapped as feedstock for other material processes. Landing spacecraft up against an unyielding embankment instead of breakaway debris barriers may not be practical; however, topography might eventually be employed in some form to reduce ongoing degradation from fine debris lofted prior to hover. supplant or supplement the other debris-mitigation measures. The certain generation of large quantities of partially-processed lunar materials is the major "hook" for successfully synergistic lunar industrial concepts.

2.5 MOBILE ROBOT CONCEPTS

This section describes the reference mobile robot concepts used for engineering analysis in this study. They are presented separately here only for clarity. As discussed in section 1.6, we developed these robot concepts together, iteratively, with concepts for the base elements they would be required to act upon, and have referred to them already many times. The primary goal was a realistically integrated, end-to-end, functional scenario.

Another goal was to discover the **minimum number of distinct machine types necessary to perform lunar surface operations**. The reason for that study emphasis is fundamental. It has become commonplace to equate mission mass with mission cost for future space programs. The reasoning is that since ETO cost is so high, every means must be found to limit the mass ultimately boosted from Earth's surface. While ETO cost is indeed high, it is far from the dominant cost share when mounting a mission. Indeed, particularly for reusable systems (a planetary surface base is "reusable" virtually by definition), reducing the DDT & E (design, development, test & engineering) cost share shows the greatest unilateral potential for program cost reduction. And the most effective way to reduce total DDT & E is to limit the number of separate hardware development efforts. The procurement structure of our space program amplifies the cost of separately accountable development efforts.

The guiding strategy of limiting the number of unique hardware systems requiring development puts our conceptual study in stark contrast to traditional terrestrial construction

scenarios, and most lunar construction scenarios based closely on that terrestrial precedent. A typical civil engineering project on Earth, such as building a highway, benefits from abundant power, cheap transportation, available servicing and task commonality with innumerable similar projects beforehand and afterwards. The result is a diverse fleet of equipment (most driven by onboard human operators), each vehicle optimized for a particular task within the overall scenario. Early efforts to conceptualize lunar construction tend to follow that example, resulting in catalogs of specialized equipment with an unacceptable total price tag.

Figure 2-18 lists the functional requirements we identified for the early lunar base. **We believe that the mission of emplacing, building, operating and maintaining a lunar base featuring investigative, mining and processing activities can be accomplished by just three vehicle types.** Each is a versatile, basic chassis which is optimized for tasks by the tools and attachments it can carry. And each is widely useful beyond the reference scenario, capable of adaptation into incrementally more advanced capabilities. For purposes of clarity, we call these three vehicle types a **rover**, a **truck** and a **straddler**. They are shown together, along with the lander and oxygen reactor, in Figure 2-19.

ROVER - This vehicle, shown in Figure 2-20, is a light transport that can be considered a second-generation Apollo LRV, featuring three fundamental differences. First, it is more robust, designed for intermittent but continual use over several years (rather than a few hours). Second, it is solar-powered, again for long-term use. Third, although optimized primarily for unpressurized crew operation, the rover is also capable of unmanned operation.

A 1 kWe, tracking array is parasol-mounted above the rover; 1 kWe, NiCd peaking batteries, trickle-charged by the array, manage demand loads for climbing and towing. A manipulator arm is front-mounted, as is a light dozer blade. The requirement for crew driving calls for higher speeds than an autonomous vehicle would typically be designed for. In fact, this smallest of our mobile robots is also the fastest. 15 km/hr on a level, prepared surface is our design benchmark. During initial robotic operation cn unprepared surfaces, the rover would move slower. (Position-based autonomous navigation has benchmarked 30 km/hr in moderate terrain where the locomotor can handle

Functions \ Tasks	Site survey	First cargo down	Cargo unloading	Landing pad prep	Road building	Transfer line deploy	PV deployment	Habitat emplacement	Regolith shelter setup	Radiator / sunshade setup	Comm system inst'l	RFC emplacement	Oxygen reactor setup	LLOX depot setup	Ilmenite mining	Ore transport	Gangue deposition	Ox reactor loading	Ox reactor dump	Ox rctr clng & servc'g	Moving disabled lander	Servicing lander	Servicing PV unit	Servicing RFC	Servicing utilities	Servicing robots
Self - Unload	●	●																								
Light mobility, materials & equipment transport	●		●		●	●		●	●	●			●								●	●	●	●	●	●
Heavy mobility, materials & equipment transport		●	●	●	●	●			●	●			●	●	●	●	●	●	●		●					
Light low - lift / positioning			●				●	●		●	●	●	●									●	●	●	●	●
Light high - lift / positioning			●					●		●	●	●				●					●		●	●		●
Heavy low - lift / positioning		●	●	●	●				●	●			●	●	●	●		●		●		●			●	●
Heavy high - lift / positioning		●	●						●				●		●		●			●		●				●
Light materials placement	●		●		●	●		●	●	●			●								●	●	●	●	●	●
Heavy materials placement		●	●	●	●				●	●			●	●				●	●		●	●		●		●
Manipulation / tool use	●	●	●		●		●	●	●	●	●	●	●	●				●	●	●	●	●	●	●	●	●
Excavation / grading				●	●		●	●	●				●	●	●		●									

Figure 2-18 Lunar surface tasks are plotted against robotic functions.
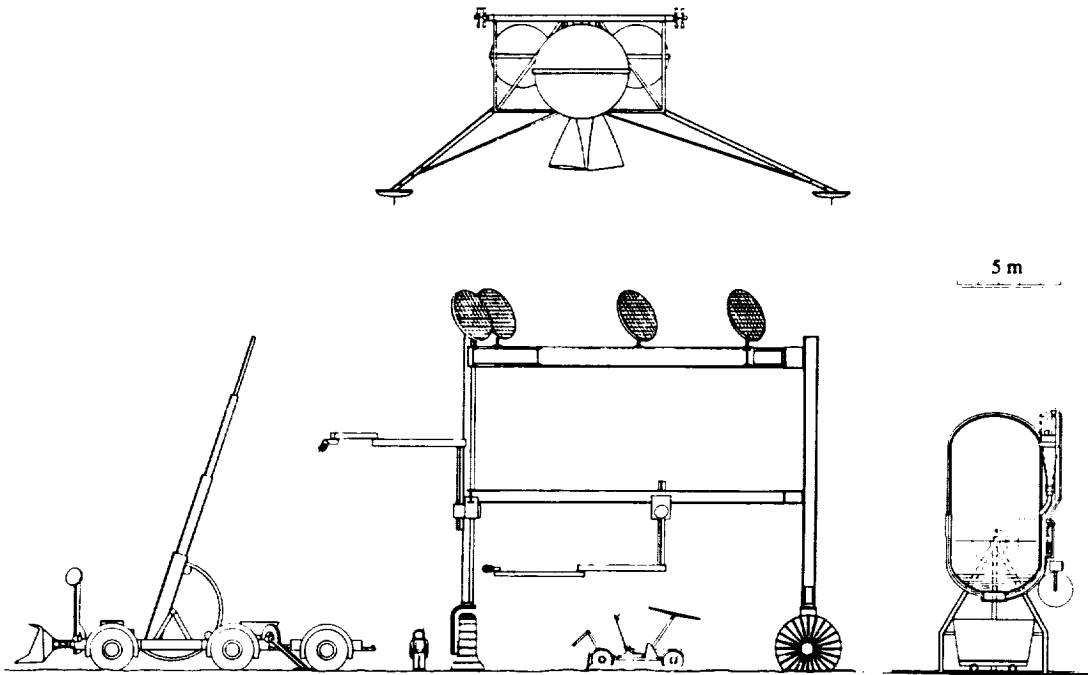
Figure 2-19 The mobile robots are adapted to all physical scales around the base.

5 m

Low - gain antenna

1 kWe GaAs tracking rigid solar array

Trunk / bin on payload bed

Manipulator

1 m

Light dozer blade

All - metal wheels

Batteries / storage

-- Based closely on successful LRV
-- Driven robotically or manually
-- Precursor surface & subsurface survey
-- Packages for Atlas-Centaur flight
-- 450 kg total

Processing / controls
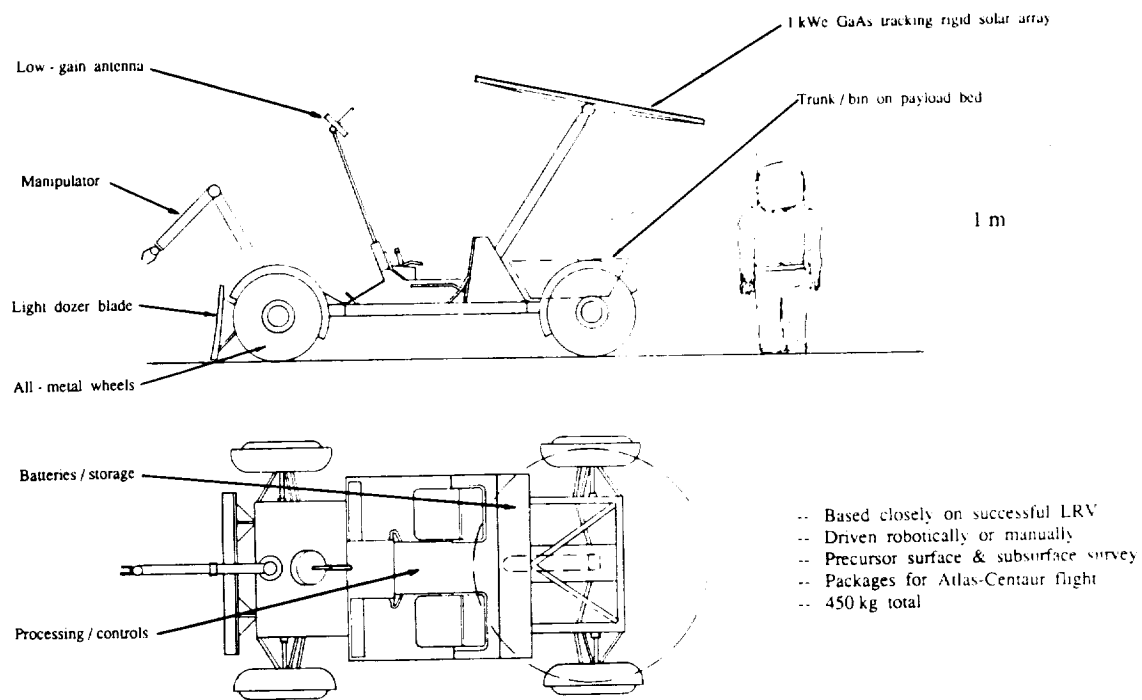
Figure 2-20 The two light rovers can be driven, or operated robotically.

the power and dynamics.) The two crew seats can be removed to accommodate attached equipment.

Two of these rovers arrive at the chosen site first, having been launched from Earth on a single Atlas-Centaur launch on a fractional-orbit direct (FOD) trajectory. They unfold, check themselves out and report back to Earth using stored power. They have video cameras, scanning laser rangers, seismic thumpers and transducers, ground-probe radar antennas (GPR), ground-pointing gamma ray spectrometers (GRS) and magnetometers, perhaps small coring drills, and an array of navigational beacons. Under supervisory control from Earth, they perform initial traverses, sending back preliminary data which will enable site planners to choose the final site and complete its detailed layout. In support of robotic base operations, the rovers then methodically traverse the entire site area, sending back copious sensor data. The efficacy of GPR in the lunar environment is still unstudied (regolithic iron may interfere; on the other hand, there is no water). However, its potential is so great that we propose it as a primary surveying tool.

On Earth, the site data are integrated and reduced into a numerical model of the three-dimensional site. Such a map would include details of surface topography and chemical composition, near-surface engineering properties, and subsurface inclusions (rocks) with resolution of order 40 cm down to the fragmented bedrock interface. Armed with such knowledge, planners can then program the base buildup to avoid intractable geological surprises. The operations robots will require less human intervention the better they "understand" their work environment, and base buildup will proceed more smoothly the more the site is characterized beforehand. The site survey is accomplished during lunar daytimes, when solar power is available. The rovers park at night, keeping their electronics warm with battery power. The overwhelming advantage of performing such a detailed survey robotically is that time can be taken as needed to accomplish it thoroughly. The resolution and extent of the site model which results is a direct function of the integration time permitted for data collection and correlation; 10 cm resolution should be possible where desirable.

Once the exact base site plan is finalized, the rovers deploy navigational beacons to aid the cargo landers arriving later. During base buildup, the rovers can expand their detailed surveying work to areas around the base contemplated for base growth. Also, being self-contained and solar-powered, they could perform extended remote scientific expeditions, although that might best wait until more than two rovers were available. When crew begin using the base, the rovers become their primary means of mobility. The downward-looking surveying equipment can be removed, and replaced with equipment and storage space appropriate for crew use. Scanning sensors would be left on, to facilitate blending EVA work with IVA monitoring and recording. With crew staying through full lunar cycles, it becomes essential to have mobility available all the time. At the beginning, short-term contingency nighttime roving can be accommodated by keeping the rover batteries charged, but extensive nighttime use would require conversion to a better storage system, probably RFC-based. The rovers' capacity for semi-autonomous navigation extends their usefulness to the crew, since the vehicles can support nominal activities more effectively, as well as perform crew-rescues not possible otherwise.

HIGH-REACH TRUCK - A mobile robot is required for intermediate jobs like: filling cavity walls with regolith; compacting roads; moving small piles of soil; helping empty out the oxygen reactors; cleaning solar arrays and radiators; positioning crew and specialized

manipulators or sensors high up on base equipment; driving into the radiation shelter access tunnel to place components requiring repair into the pressurized workshop; excavating trenches for buried fluid and electrical lines; and performing lander maintenance, including connecting conditioning and tanking lines. For all these tasks we developed an outrigger high-reach truck concept, shown in Figure 2-21.

Stabilized by up to four, corner-mounted, deployable outriggers, this vehicle can extend its boom throughout a range from the top of the tallest base element to below grade, positioning tools where needed. The boom is a four-stage telescoping beam, with triangular section (this minimizes the number of roller bearings). The fourth and third stages are slaved by cable to the second stage, which is extended by R & P drive out of the first stage. The first stage is mounted on a ring gear elevator rack, also controlled by R & P drive. The entire boom assembly is rotated on a chassis-mounted turntable by another R & P drive. Power is delivered to the boom by flexible cable; this avoids rotating electrical contacts in a dirty environment, but precludes infinitely continuous rotation of the turntable. The truck masses 6 t including boom and basic attachments, and stores 60 kWhr of energy, giving it up to 10 hr of operation on one charge. We chose NaS batteries, but RFC storage may trade favorably, especially considering commonality with power storage for other vehicles in an advanced scenario. 30 kWe is available for peak use, such as when climbing slopes, hoisting loads, or dislodging rocks. Nominal driving speed is 10 km/hr, and the machine can be handled directly by an onboard operator when desirable, although its nominal operation mode is unmanned. The center of boom motion is the safest place for an EVA crewman, so the operator station is a grilled platform on the turntable. The main control station is located on the boom gimbal mount.

The truck can move modest amounts of regolith with a small, front-mounted dozer blade, which is on-line convertible to a small bucket-loader. It is mounted on a "strong wrist", a compact pitch-roll-yaw-pitch joint which permits modest elevation changes as well as blade orientation (this way, the bucket can be used to scoop and carry small amounts of material). A small, stern-mounted bin can be used for holding attachments temporarily, or for carrying parts intended for R & R maintenance work. It features a built-in dumping mechanism to facilitate its use for carrying rocks or stones as well.

There are two important sets of attachments for the truck: towed accessories and tools for the distal end of the boom. The trailers use the same all-metal wheels,

Standard end tool mount

Top of straddler leg

3rd & 4th stages slaved by cable

Top of solar array

2nd stage racked

Triangular - section telescoping boom

Extension pinion drive

Dumping bin

Battery / controller / radiator

Ring gear elevator rack

Outrigger deployed

Gimbal mount

Outrigger stowed

Utility trailer

3 DOF strong, multi - pitch wrist mount

Elevation pinion drive

Convertible bucket - loader / dozer

Azimuth pinion drive

4 independent drive / steering wheels

Towing hitch

Operator platform

4 outriggers

5 m

-- Operated manned or robotically
-- Reach envelope: from highest site element to below - grade
-- 6 kWe average power, 30 kWe peak
-- NaS batteries or RFC, 10 hr nominal charge
-- Can place payloads in pressurized workshop via garage
-- Towed: utility trailer, bucket - wheel excavator, vibrating compactor,
      lander LOX fill - line spool - cart
-- High - reach end tools: crew bucket, fine manipulator pair, sensors,
      rock grapple, hoist, small excavator - bucket,
      oxygen - reactor maintenance set, forklift

Figure 2-21 The two high-reach trucks are versatile intermediate work machines.

suspension, axle system, and chassis frame materials as the truck, but have only passive mobility. The truck can tow more than one trailer, trained together. Four distinct trailers make up the initial accessory set. A **utility trailer** carries the menu of boom end-tools, so that special trips back to the workyard to retrieve specific items are not required in the middle of a job. A **bucket-wheel excavator** is used for digging the 1 m deep continuous trenches required for burying fluid and electrical lines. It deposits excavated regolith in a ridge alongside the trench, so that after the lines are laid, the dozer can simply push the soil back in. A **vibrating compactor** consists of a hollow metal roller, which is filled with sifted gangue in situ for ballast. An eccentric-drive motor vibrates the roller as it moves over graveled surfaces requiring compaction. Finally, a lander **conditioning cart** carries spools with electrical umbilicals and the cryogenic fill and vapor-return lines required to connect subsurface LLOX terminals with grounded landers. For base construction, this same cart receives spools carrying the coiled base utility lines to be entrenched. An optional attachment that might find use (although we did not specifically require it for our scenario) would be an auger drill; it could be mounted on the bucket wheel excavator. Only the utility trailer is shown in the figure.

The major end tools for use on the high-reach boom are: **crew bucket**, a "cherry picker" for positioning crew where needed; **hoist**, for lifting small payloads (of order 1 t); **rock grapple**, used with the hoist specifically for lifting and relocating large rocks (up to of order 0.5 m^3, depending on density); **small excavator-bucket**, to be used like a back-hoe for scooping small amounts of piled material; **oxygen-reactor maintenance kit**, for inspection and cleanout, and repairing the refractory lining inside the oxygen reactors; **forklift**, for moving small, palleted equipment packages (like spare parts) off the landers and around the base; **fine manipulator pair**, a dual set of multi-DOF arms for doing precision maintenance work; **sensor unit**, with cameras, scanners and other probes for detailed data gathering.

The configuration and dimensions of the fine manipulators are similar to a human arm. The shoulder, elbow and one wrist motion act in the same horizontal plane to minimize gravity loads, and thereby reduce the torque capacity of these joints. (The same horizontal joint geometry is used by the heavier manipulator arms on the lower frame of the straddler, for the same gravity-dependent reason. A separate vertical positioning motion allows versatile access by such horizontally-organized devices.) A total of six motions on each arm allows arbitrary orientation and positioning within the manipulators' work

envelope. The close spacing of the manipulators allows coordinated work on the same object. This configuration has proven to be highly effective for work on analogous subsea and hazardous-duty tasks on Earth.

Specific end effectors for the fine manipulator pair include: two three-fingered hands for dextrous manipulation; two parallel-jaw grippers for vising workpieces; turret tool driver with wrenches, drills, reamers, and taps; power hammer; power brush; power scraper/chisel unit; cutters; riveter unit; electron-beam (EB) unit for soldering, brazing, welding and plating; and electrostatic precipitator for removing dust films from PV units and radiators. The nomenclature used here is intended to convey functional uses required rather than specific effector designs. For example, a riveter for use with memory-metal rivets might be a heating mantle shaped for the rivet heads, rather than a mechanical upset tool. Paired combinations of these effectors can accomplish an enormous variety of preprogrammed and telerobotic tasks. The toolbox containing these devices, and accessible to the manipulator arms, must be accompanied by supplies of solder wire, welding rods, appropriate fasteners, binding and electrical wire, and provision for specific replacement parts.

The truck chassis is clearly adaptable for other uses not specifically called for by our limited scenario. With its large frame and 2 m-diameter wheels, the truck could even be used as the core of a pressurized rover for advanced scenarios. Combining a boom-less chassis with a common spacecraft crew cab and cryogenic fuel cells would accommodate long-duration ground excursions without requiring a full-scale rover development program. As with all mobile robots, we anticipate the need for a minimum of two trucks at the early base. For many tasks, each will work in support of a straddler.

STRADDLER - We require two straddlers, shown in Figure 2-22, for the initial base. These versatile vehicles are optimized for those jobs which clearly exceed the human scale: offloading landers and moving empty landers; carrying heavy or bulky elements around the base; positioning elements requiring deployment or assembly; mining, moving and depositing lunar soil and process materials. They have no provision for regular onboard human operation, although in a more advanced scenario they could carry a small, pressurized crew cab to facilitate line-of-sight teleoperation. Assembled in LEO from a few

Wheel

Footprint

Dynamic array
envelope

9 fixed hoists

2 9-DOF
manipulators

Open space

Manipulator
elevation rack

Lower stabilizing frame with
conunuous manipulator rails

Sealed brushless
DC hub motor

All-metal
band-wheels

5 m

Wheel yoke

Battery / processing

12 1-kWe GaAs rigid
tracking solar arrays

Leveling rack

Battery / processing

Composite upper structural frame

Composite leg column

Splined
steering
unit

-- Mobile gantry, transport, miner, power utility
-- Modular, assembled in orbit, landed intact
-- 12.5 mt total mass, 30 mt maximum capacity
-- 35 kN total drawbar pull
-- 10 cm / s creeping speed, 30 cm / s cruise speed

Figure 2-22 The two straddlers perform heavy lifting and transporting tasks.

large parts and brought to the Moon intact, each simply drives itself off its delivery lander. Being solar powered, they operate only during the lunar daytime; they can also act as mobile power utilities if needed.

Albeit an unconventional vehicle concept for lunar base studies, the straddler is a seemingly inevitable outgrowth of several inescapable requirements. We addressed particularly the "first landing problem". In our scenario, the first landing after the site survey precursor is a cargo flight; it must unload itself with no assistance from people or any local equipment, in an unprepared environment. The functions of unloading heavy (up to 30 t), bulky (4.5 x 16 m) payloads from elevated locations such as the lunar lander, transporting them several hundred meters across the surface, unloading them from that transporter, emplacing them precisely, and doing it all carefully, must be accommodated by any tenable scenario and are far beyond the physical capacities of human crews. It seemed sensible to combine the capabilities for these diverse tasks in one machine. Finally, accepting a machine concept like this practically solved all our open operational requirements problems. We found other cases, such as unfolding large-area solar panels, assembling shelter sections (Figure 2-23), mining regolith, loading oxygen reactors, and moving crippled landers, which a large mobile crane like the straddler served quite well.
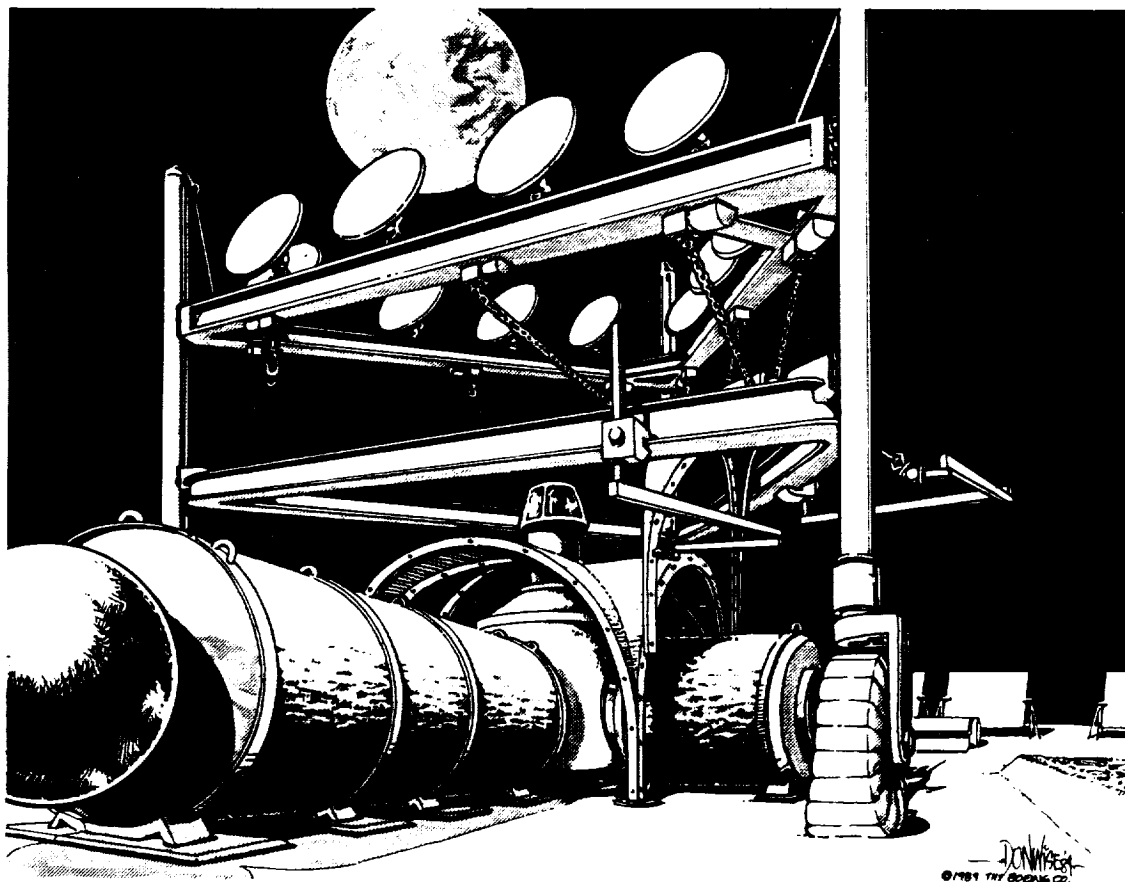
Figure 2-23 The straddler assembles large sections of the habitat shelter.

The best form for an extraterrestrial mobile gantry is a complex issue, on which we devoted considerable effort. Important requirements seemed to be: minimizing part count and complexity; maximizing geometrical envelope and access to workpieces; accommodating a wide range of vertical positioning; including capacities for heavy lifting, omni-directional mobility and fine manipulation; and facilitating leveled travel over unprepared, cratered planetary surfaces. A fundamental design trade is the number of legs such a device should have. Figure 2-24 summarizes our discussions of this issue; we settled on the equilateral triangular plan.

The straddler stands 20 m high when unloaded, with a wheelbase of 20 m. Its two horizontal, open triangular frames ride vertically on three columnar legs with captive R & P drives. Independent leg motion allows the robot to be self-leveling on uneven or sloping ground. The top, "strong" frame carries a dozen tracking, 1 kWe PV arrays,

peaking batteries and onboard processors, communication equipment, lights and sensors, a manipulator end-effector toolset, and 9 fixed cable hoists with which to lift, position and carry payloads massing up to 30 t. The lower, "light" frame stabilizes the vehicle laterally, and is the manipulator track. Two 9-DOF manipulator arms travel around a continuous rail on this frame. Each can reach beyond the middle of the straddler envelope from any perimeter point, below or above the top frame. The lower frame also deploys jacks to the ground, which allows lifting a main leg for maintenance. The boom truck can reach systems at the top of the straddler for repair, and one straddler can assist in rescuing or repairing the other.

Each drive unit is independent; separate brushless DC motors provide motive power in the wheel hubs, and steering at the leg bases. The metal band-wheels are envisioned as different from the helically-wound wheels used on the rover and the truck. The straddler wheels undergo large deformation when the vehicle is loaded heavily, to maintain sufficient flotation even on unimproved lunar soil (7 kN/m^2 is the pressure resulting in a few centimeters of settling in intercrater surface regolith). Controlling the wheels' intrinsic compliance during precise payload positioning maneuvers is an important issue; deployable anchors mounted on the wheel yokes may be required to act as stabilizers. Power and control lines connecting the top frame to the drive units are coiled within each hollow, tubular leg. Basic structural members are made of coated carbon composites; high-stress parts like the leg racks, pinion gears, manipulator rails and rollers, and wheel yokes are of titanium. Maximum vehicle speed is 30 cm/s; when mining or positioning large payloads, "creeping motion" of 10 cm/s or less is used to limit dynamic effects and maximize available torque. This speed regime lies outside the range of productive human "driving"; hence apart from handholds and foot restraints (for inspections and troubleshooting), there are no provisions for onboard crew. Teleoperation, when necessary, is accomplished in the reference scenario from remote stations: inside the pressurized control center, or from a slave panel located on a truck or EMU belt-pack.

The large, stable frame, autonomous navigation capability, and large load capacity of the straddler pre-adapt it for many uses not specifically called for by our simple scenario. During periods of planned downtime, or during non-critical activities when the "backup" straddler can be spared away from the base, scientific excursions could be performed (within the constraints of its roughly 1 km/hr top travel speed). The straddler's unique

Straddler Concept Rationale:

In comparison to crane-type lifting/construction equipment, the Straddler concept has several significant advantages:

- Bridging of loads:
  - Minimizes internal forces and therefore structure; maximum lift to weight ratio.
  - Precludes gross tipover; CG of load is always within contact polygon.
- Array of simultaneous lift points possible.
- Provides frame for rigging/fixturing/jigging components during assembly/construction; scaffoldless construction.
- Self-unloading from lander

Straddler Configuration Rationale:

	ADVANTAGES	DISADVANTAGES
Three legs	• Determinate contact with ground – simplified control and mechanism model. • Fewer parts and therefore potentially greater reliability	• Non-conventional triangular frame may result in heavier structure if moving gantry crane is used. • Triangular contact polygon suboptimal for rectilinear mining operations.
Four legs	• May be better for excavation tasks where straddling of large span transverse to direction of travel is desirable. • 4th leg set may provide functional redundancy	• Indeterminate contact with ground requires active leveling to maintain wheel contact (more complex control). • Frame wracking more likely

Figure 2-24 The straddler's abilities and configuration were traded.

features would permit large or extensive sample collection, as well as deep drilling. Its large envelope would make it useful as a mobile testbed for a variety of ISRU engineering investigations of native material (such as rock-melting and in-situ sintering).

MINER / BENEFICIATOR - The feedstock material we need is the mineral ilmenite ($FeTiO_3$). As far as we know, its occurrence in lunar rocks and soils is not concentrated, so it does not represent a conventional ore. Extracting it involves processing large amounts of native material. For reasons not entirely understood, its abundance may be higher in the parent basaltic rock than in the comminuted regolith. The choice of baselining basaltic or regolithic feedstock is fundamental. Moving soil around is required for any base buildup concept, whereas basaltic feedstock would require extra resources of equipment, energy and time for removing the regolith overburden, breaking up and moving rocks, and crushing them. The marginally greater yield from basaltic feedstock would come at a high cost, so we chose regolithic feedstock. Ilmenite abundances between 7.5 and 10 % by weight are commonly quoted for mare soils. Operational scenarios cannot be based on "as high as" values, however. For the quantitative purposes of this study, we baseline 7 % weight fraction of ilmenite in lunar regolith.

The comparatively shallow regolith layer (ranging from a few to about 30 m deep) precludes open-pit mining for extended production, but constrains us instead to a horizontally organized strip mining method. The relative density of undisturbed lunar regolith is unprecedentedly high for soil-mining operations. Using familiar methods (front shovels, dumptrucks and dozers) would require levels of mobile power that an early lunar operations scenario just could not provide. Most likely, advanced lunar equipment eventually will use fuel cell plants, tethered power from fixed nuclear generators, or perhaps onboard reactors for high-power mobile process plants. But limiting our source to solar power, as we can for this study, constrains the rate and type of excavation that a mobile robot can reasonably achieve. Our modest excavation rate (of order 1 kg/s to support 100 t/yr of LLOX production --- approximately equivalent to a "good guy with a shovel"), and the rather homogeneous character of mare regolith, together make possible another approach. We envision a mining method analogous to plowing or grading, which matches the horizontal geological constraint of the site discussed above. By plowing thin layers of regolith, rather than scooping up deep bucketfuls, we take advantage of the regolith's predictability, accommodate its high relative density, avoid the need for massive mobile power sources, match the other mobility requirements of the straddler, and directly produce a flat, exposed table of undisturbed regolith for foundation use.

We developed our operations concept to use a self-contained mining attachment carried by the straddler (Figure 2-25). Since working a site in thin horizontal layers necessitates relocating excavated material, the miner is designed to separate usable constituent fractions as they are transported to different destinations. This minimizes the total work done on each excavated particle. When mining, the straddler follows a course designed to avoid intractable inclusions like outcrops or immense boulders, based on the subsurface surveys. The truck working with the straddler takes care of movable rocks. Singular rocks too large to move, but too small to warrant planning the site around, can be fragmented explosively prior to mining, making them removable by the truck. One advantage of mining in mature regolith is that such obstructions can be expected to be relatively infrequent. As the miner advances, a "cowcatcher" excludes **rocks** larger than 10 cm. The cutting tool crowds material smaller than 10 cm in size into a 1 m^3 hopper for about 11 continuous minutes (a small dozer blade grades the soil surface on the first pass). This hopper is hoisted to the top of the miner stack and is dumped into a hold-up bin, then resumes mining. A grizzly scalper removes and bins **stones** larger than 2 cm. Two layers of vibratory sieves separate **gravel** (> 2 mm) and **sand** (> 0.5 mm), which

are both binned. Using six sieve trays per layer allows them pivoting clearance, important for de-clogging. Periodically, the trays are inverted and "spanked" by a tamper mechanism. The vibrator stack housing the sieves is dynamically isolated from the rest of the miner, both above and below. Fines less than 0.5 mm then fall through a magnetic separator, where the paramagnetic **ilmenite-containing particles** tend toward one side. The efficiency of magnetic separation appears lower than some past work had hoped. We assumed a conservative outcome of 55 % ilmenite enrichment. These fines fall into one bin, and the leftover **gangue** into another. Periodically, electromagnets in the separator are energized to remove particles stuck to its permanent ceramic magnets. By hoisting the miner up, the straddler can position any bin over an appropriate dump point, such as a deposition berm or a roadside hopper.
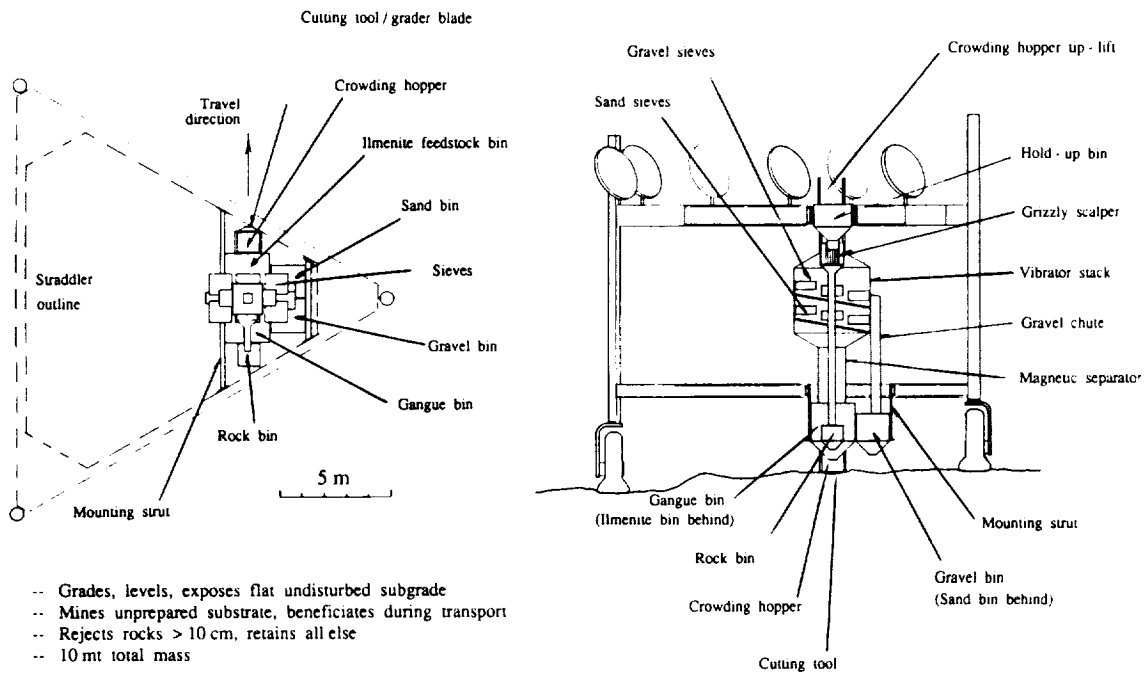
Figure 2-25 The miner / separator is an integrated unit carried by the straddler.

/

The combined system consumes of order 10 kW and masses 10 t. It has been configured to permit robotic access to motors and actuators from around the outside. The design tool bite is 5 cm deep by 30 cm wide. Moved forward at 10 cm/s, the tool covers a 1.8 m^2/min swath, and excavates 1382 t of raw material in a full 300 hr lunar day. 5/6 of the time is spent excavating and "steering"; the rest is spent carrying collected material to deposition sites. The separated fractions expected are discussed in section 3.1. The overwhelming amount of gangue dominates the deposition schedule. We sized the bins for stones, gravel, sand and feedstock to hold enough to last through 4 gangue dump-trips before they too need emptying. This optimizes non-excavation transport time.

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3. OPERATIONS ANALYSIS

The "operations" on which this study focused are those involved in building up the initial base. Included are various combinations of activities in the following categories: landing, surveying, sensing, navigation, communication, safing, conditioning, tanking, offloading, transporting, transferring, repackaging, positioning, emplacement, connection, excavation, beneficiation, deposition, processing, inspection, verification, testing, removal, replacement, and repair. We consider that operations involved strictly in running the base once built, and expanding it after that, do not require tasks more complex than those required by the buildup and just enumerated, and in fact those later operations can presume to benefit from more regular human presence. The first robotic emplacement and qualification tasks are the toughest challenge.

3.1 BUILDUP SCHEDULE

The base is built in four phases: spaceport, habitat/workyard area, industrial production site, base expansion. The boundaries between phases, however, are somewhat blurred for two reasons. First, the most efficient construction schedule actually results from building some base-wide sitework infrastructure first. Burying fluid and electrical lines is an example, since it should precede paving and since such lines connect elements belonging to different phases. Second, material required for some phases is only available from other phases. (For instance, the sitewide average excavation depth is 0.27 m, and the average paving thickness is 0.04 m, 15 % of the average excavation depth. But gravel and sand together constitute only 11 % of the excavated material, so paving material is a driving commodity. In particular, the gravel and sand required to pave the reactor area and spaceport road must come from base expansion site-clearing. We felt this "losing" inequity between generation and use was acceptable at a time when base expansion was certain and close. Later on, matching resource generation with product utilization
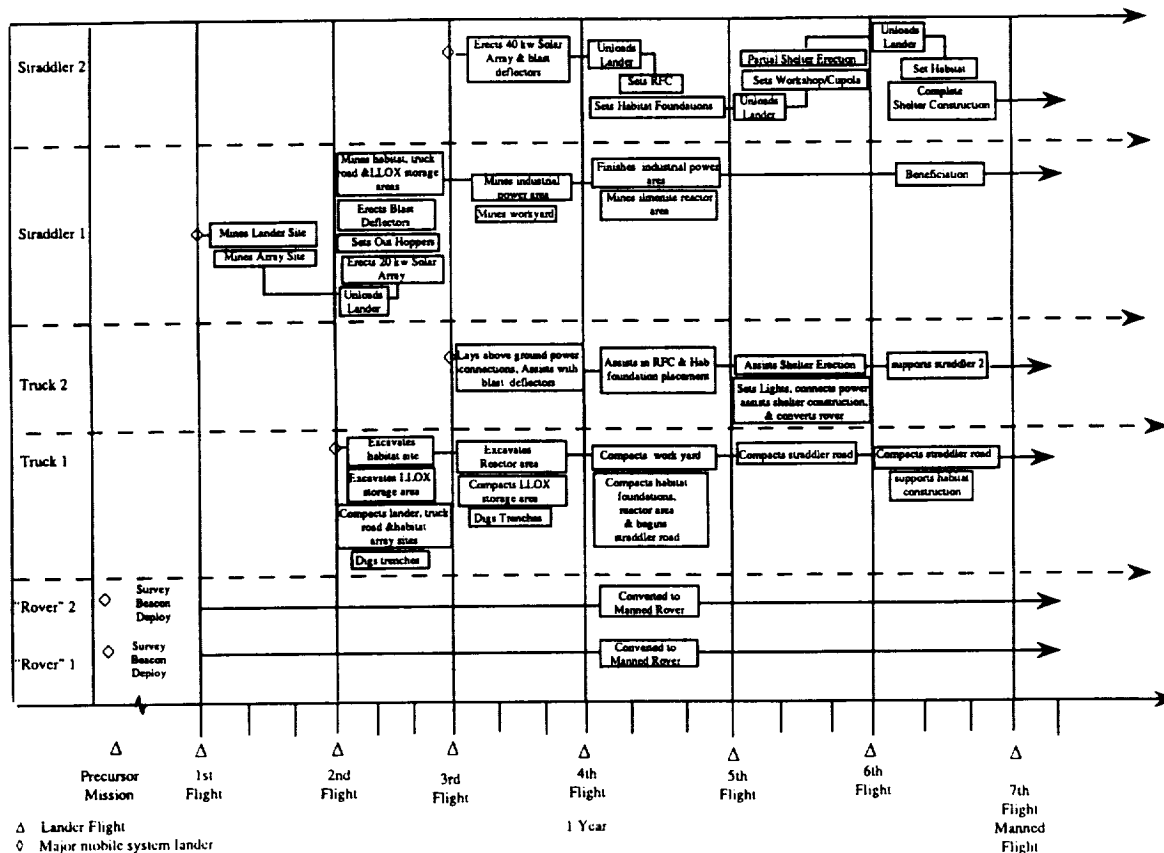
Figure 3-1 *Summary robotic operations sequence prioritizes vehicle tasks for the entire base buildup.*

more closely would be advisable.) However, for organizing a discussion of base buildup, the four-phase breakdown is generally useful.

The landing pad is completed first (cleared, underground lines installed, graveled, compacted, beacon installation completed and the most critical blast deflectors erected). This provides a predictable landing surface for subsequent flights, and limits blast-debris contamination of solar arrays and habitat radiators at the earliest opportunity. The habitat and supporting facilities (arrays, RFC module and shelter) are erected on cleared and (where required) graveled and compacted surfaces. This enables productive, radiation-safed crew visits at the earliest opportunity. Then, the extensive deployment and preparation of industrial facilities enables LLOX production to begin, introducing use of lunar resources at the earliest opportunity. Since the Earth-based portions of the transportation architecture can already support landings without LLOX usage, the most immediate benefit from LLOX will be to allow increased cargo payloads to the surface.

Straddler 2: Planned Down Time | Sets LOX Discharge Cart; Sets 100 kw Solar Array & Base Power cond. unit; Unloads Lander | Unloads Lander; Sets RFC | Unloads Lander; LOX Storage Area Assembly | works on plant; Erects OX Plant 1; Unloads Lander | planned down time, manned mission | Unloads Lander; Erects 110 kw Solar Array & blast deflectors | Unloads Lander; Erects OX Plant 2 & Assists operations of Plants 1 & 2 | Unloads Lander; Erects OX Plant 3 & Assists in operation of all Plants | Operates All Plants

Straddler 1: Beneficiation | Planned Down Time | Beneficiation

Truck 2: planned downtime; Assists in compacting the industrial power area | Sets LOX Plant Tracks; Sets Power Control Station; planned downtime | Assists in RFC emplacement & power connections | Assists in LOX Storage Area Assembly | Assists in OX Plant 1 Erection & operation | Assists in OX Plant 1 operation | Assists in OX Plant 1 operation | Assists in OX Plant 2 erection Plants 1 & 2 operation | Assists in OX Plant 3 Erection & operation of all Plants | Assists in all Plant operations

Truck 1: Compacts industrial power area | Compacts industrial area & supports straddler 1 | planned downtime; support to straddler 1 as required | Assists in LOX Storage Area & straddler 1 | Supports straddler 1 as required | Supports straddler 1 as required; planned downtime | Assists in solar array set up; lays cables & grounds | Connects OX Plant 2 electrical connections; Assists in OX plant operations | Assists in all Ox Plant operations

Rover 2: Manned Rover

Rover 1: Manned Rover

Timeline markers: 7th Flight Manned Flight | 8th Flight | 9th Flight | 10th Flight | 11th Flight | 12th Flight Manned Flight | 13th Flight | 14th Flight | 15th Flight | 16th Flight Manned Flight

Figure 3-1 (Continued)

(We should not expect crew missions to **depend** on lunar retanking until much later.) Finally, with the early base both habitable and productive, growth enables it to become a robust outpost capable of supporting continuous occupancy, with improving redundancy and self-sufficiency, at the earliest opportunity.

Priorities for excavation and paving are based on three goals. First is limiting loose dust around the base, which would complicate the operation, and compromise the reliability, of base systems. In particular, the landing pad needs to be paved with gravel alone, and the areas around critical components require paving with a mixture of gravel and sand. Second is providing a consistent surface for ground transportation. This is required for predictable performance and repeatable navigation, and is served adequately for the designed traffic rates by roads paved with a mixture of gravel and sand. Third is meeting the demand sequence of construction by preparing foundation surfaces and dust-free paving as needed (spaceport, habitat power plant, habitat complex, LLOX depot,
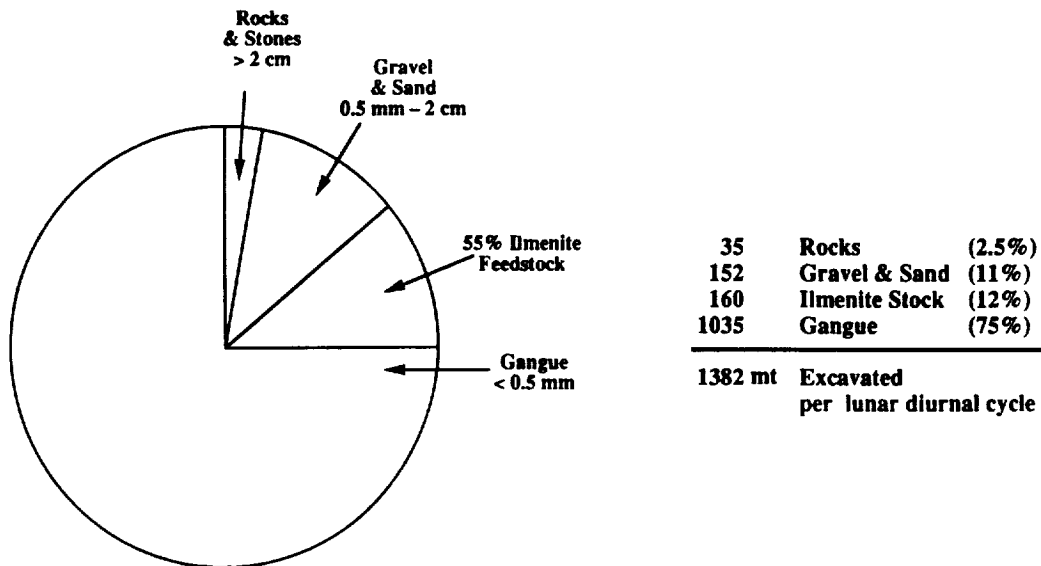
Figure 3-2   Expected regolith constituent fractions are based on Apollo data.

workyard, oxygen reactor field, roads and industrial power plant). Fourth is accommodating utility installation first. After facility foundation surfaces are dug, trenches for burying fluid and electrical lines are excavated at once by a truck towing the bucket-wheel trailer. The lines are laid immediately and buried, before the foundation areas are graveled over and compacted. Line ends are left exposed (but sealed against contamination) above ground level for connections to be made later. The ends are flagged to aid the mobile robots in avoiding them when graveling and compacting the surrounding area. No connections are buried, since re-excavation would be as tedious as an archeological exhumation.

Our operations analyses concentrated on a classical task/time/resource analysis of base and production facility buildup, tied to both the robotic equipment and flight schedule. An event logic network was created and analyzed to schedule the operations and uses of equipment. The top-level network is shown in Figure 3-1. Quantitative results are coupled closely to flight rate, excavation rate, regolith composition, lunar resource production rate, and frequency of crew-carrying (cargo-less) landings. Once again, delivery assumptions are: 4 landings/yr, with cargo flights bringing 30 t each. In all, 390 t of equipment is required from Earth, as well as 2 crew-carrying flights. (For clarity the flight manifest is discussed separately in section 3.2.) Figure 3–2 shows expected mare regolith constituent fractions, based on published analyses of Apollo data.

Assume: 13 28d diurnal cycles per year available
12 cycles working time, 1 cycle down
100 t LLOX total production (875 m³) per year
3 oxygen reactors, each produces 33 t/yr
1.7 t/m³ piled bulk density
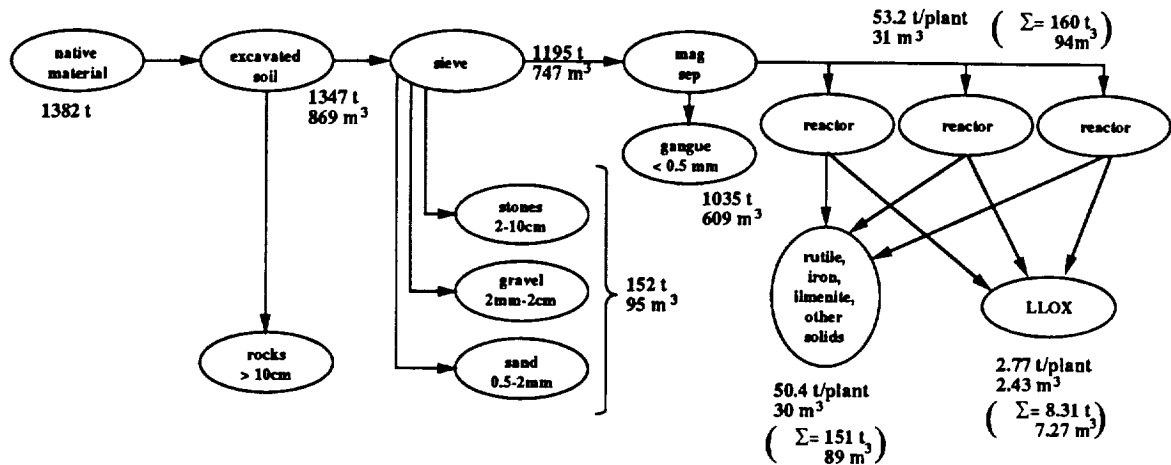
Figure 3-3   *LLOX production drives the required excavation rate.*

Figure 3-3 derives from these data the overall excavation rate (1382 t/cycle) required to support a 100 t/yr LLOX production rate, as well as the resulting quantities of material flowing through the beneficiating process.

Figure 3-4 shows equipment design requirements to match such excavation rates. In our scenario, base construction is constrained to utilize the machine capabilities design-driven by LLOX production. However, the use of the mining straddler is driven in the initial buildup period by the needs for site clearing and gravel production, rather than by the need to produce reactor feedstock. (Indeed the oxygen reactors which consume the ilmenite feedstock are virtually the last pieces of base equipment to arrive. They are brought when the utility and sitework infrastructure is already complete.) A "fringe benefit" from all the site preparation activity before their arrival is a 2.5 yr stockpile of reactor-ready ilmenite feedstock, which can be relied on as an operations cushion later.

Other important assumptions are listed below for convenient reference:

1)   A reference travel distance of 415 m separates the spaceport and the workyard.

Straddler/Miner Assumptions

Tool bite: 5 cm deep x 30 cm wide
Tool speed: 10 cm/s
Duty cycle due to material dumping: 5/6
Duty cycle due to steering & rocks: 3/4
Day length: 300 hr
Lunar cycles available per year: 12 (13th for downtime)

Results

m^2 of single passes	per unit time
67.5	hr
20250	300 hr cycle
60750	interval between lander flights
243000	yr

1013 m³ material removed ——► 1320 — 1920 t/cycle
depending on native depth
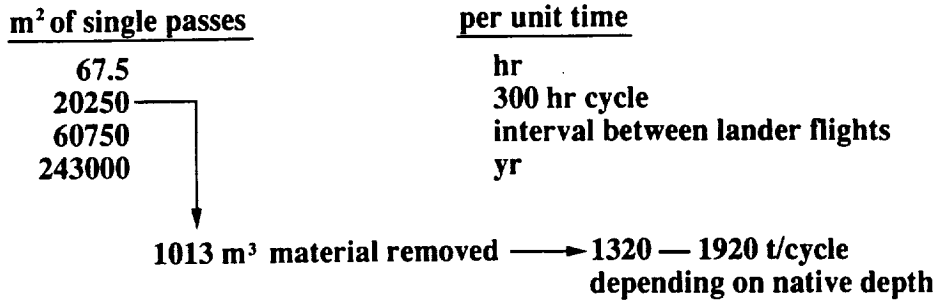
All throughput calculations based on 1382 t/cycle

Figure 3-4   *Miner design requirements were developed to match the excavation rate.*

2)   All major operations are conducted during lunar daylight only. Once the oxygen reactors are brought on-line however, activities associated with emptying, cleaning, inspecting, and refilling them are conducted by the mobile robots using stored power in the lunar pre-dawn hours.

3)   Work can, when necessary, proceed during the full 336 hr of lunar daylight. In general, however, we limit each vehicle to a maximum schedule of 300 hr of activity plus 8 hr for startup, checkout and shutdown. The other 28 hr are reserved for contingency.

4)   Landers arrive nominally 48 hr into the daytime portion of a lunar cycle, due to lighting angle constraints for pilot (whether onboard or telepresent) visibility. With terminal guidance beacons in place, this can be regarded as a "soft" requirement, used only for consistency in the timeline analysis.

5)   The regolith densities assumed for calculations of excavation and deposition quantities were: undisturbed, subsurface density = 1.9 t/m^3

initially deposited density = 1.5 t/m^3

compacted density = 1.7 t/m^3

piled deposited density = 1.7 t/m^3

This was intended as a first-order acknowledgment that bulk density of lunar regolith depends on its processing history. The "piled" figure refers to a deposited layer several meters deep, subject to substantial overburden weight.

6)   Virtually all excavation is accomplished by the mining straddler, which beneficiates the material it removes. Excavation of those areas requiring 1 m depth (foundations for the habitat system, oxygen reactor field and LLOX depot), however, is accomplished by both the mining straddler and a truck. Using its dozer/bucket, the truck merely relocates unbeneficiated material off to the sides of the worked area.

7)   When a truck augments a mining straddler for local regolith-moving, the truck's average excavation rate is 54 m^2/hr at 5 cm cutting depth per pass. This includes time lost to steering, and a 2/3 duty cycle for recharging.

8)   The average straddler excavation rate is 67 m^2/hr at 5 cm cutting depth per pass, including a 5/6 duty cycle due to dumping trips, a 3/4 duty cycle due to steering losses and rock removal, and a 10/11 duty cycle due to lifting material into the miner stack.

9)   The gravel/sand compaction process requires 2 passes by a truck towing the vibrating compaction roller.

Figure 3-5   combines the machine capabilities with quantified site plan data to derive the site preparation effort required to construct the reference base. Table 3-1 breaks this excavation and paving effort down into a schedule of task periods adapted to the availability of equipment and the arrival of flights. It covers the effective base construction time: the first 23 lunar cycles, or almost 8 flight intervals. The commodity of interest is paving gravel/sand, which is measured in 27 t hoppersful.

Assumptions: __Clearing__ 5 cm cutting depth per pass
Final depth = 0.2m (4 passes) nominal
= 1.0m (20 passes) as noted by *
Excavation rate = 67.5 m² single pass/hr

__Paving__ Compacted gravel/sand bulk density = 1.7 t/m³
Deposited layer 5 cm deep after compaction
27 t hopperful⟶318 m² finished area

	Area (m²)	Clearing Time (hr)	Gravel (t)	Hoppersful
Spaceport				
Central pad	5125	304	436	16
LLOX depot foundation	750*	223	64	2.4
Unpaved border	3800	225	—	—
Straddler road	8000	474	680	25
Truck road	800	47	68	2.5
Base Center				
Hab foundation	1200*	355	102	3.8
Hab power area	2775	164	236	8.7
Unpaved power area	720	43	—	—
Workyard	6113	362	520	19.3
Industrial Plant				
Ilmenite reactor area	2100*	622	179	6.6
Power plant roads	9000	533	765	28
Unpaved power area	4800	284	—	—

Figure 3-5 *The equipment capacities and the site plan together determine the base site preparation schedule requirements.*

A cycle-by-cycle schedule of activities spanning all 45 cycles of the 15-flight buildup scenario, from the first landing all the way through full oxygen production, is tabulated in Table 3-2. These schedules reflect the excavation rates and workload for the daylit portion of each lunar cycle. After the first 23 cycles, the workload is reduced to the point that most of the time the vehicles are idle, and available for contingency or exploration purposes. This appears graphically in the timelines of Figure 3-6, which represent only the most active periods (cycles 1 - 18 and 28 - 30) of base construction and indicate the amount of planned vehicle downtime. Only rarely does the amount of contingency time appear as though it might be inadequate. Base buildup is constrained by the inflexible flight rate to be rather hectic near the beginning, and rather light toward the end. A modest ability to relax the rigid flight schedule could enhance contingency opportunities near the beginning (when they are likely to be needed more), and enhance base productivity as the transition to operational status is made (when efficiency becomes paramount).

Crew visits are scheduled at strategic points in the overall buildup. The first crew visit is the 7th flight (19th lunar cycle AFL). Primary goals are to verify and adjust the

Lunar Cycle	Lander Flight	Area Cleared	Area Paved	Gravel deposited (hoppersful)	Gravel stored (hoppersful)
1	1	Lander Area (central pad, unpaved border & access road)	Lander Central Pad	5.6	....
2		Lander Area	Lander Central Pad	5.6	....
3		Lander Area	Lander Area / Depot	5.0 / 0.6	
4	2	Lander Area	Truck Road	1.9	3.7
5		Habitat Array	Habitat Array	8.7 *	0.6
6		Habitat Area/ Depot	Habitat Array / Lander Area / Depot Truck Road	5.0	1.2
7	3	Workyard	LOX Storage	1.8	5.0
8		Workyard / Industrial Power	Workyard	5.6	5.0
9		Industrial Power	Workyard	5.6	5.0
10	4	Industrial Power/ Reactor Area	Workyard	5.6	5.0
11		Reactor Area	Workyard/ Reactor Area Habitat Area	3.1/ 2.5 3.8 *	1.2
12		Base Extension	Reactor Area/ Straddler Roads	4.1/ 1.5	1.2
13	5	Base Extension	Straddler Roads	5.6	1.2
14		Base Extension	Straddler Roads	5.6	1.2
15		Base Extension	Straddler Roads	5.6	1.2
16	6	Base Extension	Straddler Roads	5.6	1.2
17		Base Extension	Straddler Roads/ Industrial Power Area Access Roads	1.1/ 4.5	1.2
18		Planned Downtime			
19	7	Base Extension	Industrial Area Access Roads	5.6	1.2
20		Base Extension	Industrial Area Access Roads	5.6	1.2
21		Base Extension	Industrial Area Access Roads	5.6	1.2
22	8	Base Extension	Industrial Area Access Roads	5.6	1.2
23		Base Extension	Industrial Area Access Roads	1.1	5.7

* Deposition tasks requiring < 5.6 hoppersful result in gravel storage for later use.

Deposition tasks requiring > 5.6 hoppersful tap the stored surplus

Table 3-1   *The excavation / paving schedule is keyed to material availability and the flight manifest.*

Straddler 1	Straddler 2	Truck 1	Truck 2

1st Lunar Cycle

> Flight 1
> Lander
> Arrives with
> Straddler #1
> Miner Box
> 5 Hoppers

Straddler 1 (1st Lunar Cycle):
- Straddler c/o
- Straddler extends legs, removes itself, miner box, and hoppers.
- Straddler moves all cargo to a safe distance
- Lander takes off
- Straddler sets out hoppers
- Begins mining/ beneficiating landing area (includes central pad, unpaved border, straddler road)
- Gravel is deposited near the cleared area as needed
- Gangue is deposited at shield wall location

Truck 1 (1st Lunar Cycle):
- Preparation for shutdown
- Shutdown for night

2nd Lunar Cycle

Straddler 1:
- Straddler startup and c/o
- Continues mining/ beneficiation landing site

Truck 1:
- Rover deploys beacons at landing site
- Preparation for shutdown
- Shutdown for lunar night

3rd Lunar Cycle

Straddler 1:
- Straddler startup and c/o
- Continues to mine landing area
- Straddler sets down miner box, inspects it and does routine maintenance

Truck 1:
- Straddler prep. for lunar night
- Shutdown for lunar night

/

4th Lunar Cycle

> Flight 2
> Lander arrives
> with truck,
> truck/rover
> packages,3 hoppers,
> spares and stores,
> 20 kw solar array,
> vibrating roller,
> 5 blast deflectors,
> bucket wheel can,
> cables and plumbing
> for burying and
> LLOX valve box

Straddler 1 (4th Lunar Cycle):
- Straddler c/o and startup
- Straddler removes cargo to safe distance
- Lander takes off
- Straddler temporarily erects 20 kw array on unprepared site
- Straddler sets out hoppers
- Straddler attaches miner box
- Straddler finishes mining landing area

Truck 1 (4th Lunar Cycle):
- Truck 1 deployed and c/o
- Truck excavates habitat level down 0.5 meter

Truck (4th):
- All vehicles shutdown for lunar night

5th Lunar Cycle

- All vehicles c/o and startup

Straddler 1 (5th Lunar Cycle):
- Straddler beneficiates / mines habitat array area (paved and unpaved)
- Straddler beneficiates/ mines truck road
- Straddler deposits gravel at the landing central pad area and truck road
- Straddler sets down miner box
- Straddler erects blast deflector

Truck 1 (5th Lunar Cycle):
- Truck excavates LOX storage area down 0.5 meter
- Truck fills vibrating roller and attacheds to it
- Spreads gravel and compacts lander central area and truck road
- Vehicles shutdown for lunar night

6th Lunar Cycle

- All vehicles c/o and startup

Straddler 1 (6th Lunar Cycle):
- Straddler moves 20kw solar array and erects it on prepared area
- Straddler attaches miner box
- Straddler clears final depth of habitat area (0.5 meters deep)
- Straddler clears final depth of LLOX storage area (0 5 meters deep)
- Straddler deposits gravel at habitat array area

Truck 1 (6th Lunar Cycle):
- Truck finishes spreading gravel and compacting the lander central pad and truck road area
- Disengages vibrating roller & attaches bucket wheel
- Truck digs power trench, lays cables and covers trench from power area to habitat
- Disengages bucket wheel and attaches compactor
- Compacts habitat array area
- Begins excavation of ilmenite reactor area

- All vehicles park clear of the landing area
- All vehicles shutdown for lunar night

Table 3-2 *Activity schedules plan major vehicle tasks throughout the buildup period.*

Straddler 1	Straddler 2	Truck 1	Truck 2

——— 7th Lunar Cycle ———

> Flight 3
> Lander arrives with truck 2, straddler 2, 40 kw solar array, truck /rover adapter packages, tool cart, 4 blast deflectors
>
> Unloads itself and cargo to safe distance
>
> Lander takes off

Straddler 1	Straddler 2	Truck 1	Truck 2
• Straddler 1 c/o and startup • Straddler 1 beneficiates workyard • Gravel deposited at LLOX storage area Note: Stores 4 hoppers of gravel for the habitat foundations	• Sets up 40 kw solar array • Erects blast deflectors • Dumps partial gravel hopper at LLOX storage area	• Truck 1 c/o and startup • Finishes excavation of ilmenite reactor area down 0.5 meters • Disengages compactor & attaches bucket wheel • Digs trenches, lays cable and pipes form the storage, reactor and power areas, then covers the trench	• Truck 2 deployed.c/o and startup • Assists in array setup and above ground power connections • Assist in erecting blast deflectors as required
		• All vehicles prepare for shutdown	
		• All vehicles shutdown for lunar night	

——— 8th Lunar Cycle ———

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup • Straddler finishes beneficiation workyard area • Starts beneficiation industrial power area • Gravel deposited at workyard	• C/o and startup • Planned down time	• C/o and startup • Finishes trenches between areas • Disengages bucket wheel &engages compactor • Spreads gravel and compacts LLOX storage area foundation	• C/o and startup • Planned down time
		• All vehicles prepare to shutdown	
		• All vehicles shutdown for the lunar night	

——— 9th Lunar Cycle ———

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup • Continues beneficiation of industrial power area • Gravel deposited in the workyard	• C/o and startup • Planned down time	• C/o and startup • planned down time • Compacts gangue barrier as required	• C/o and startup • Planned down time
		• All vehicles prepare to shutdown	
		• All vehicles shutdown for the lunar night	

Straddler 1	Straddler 2	Truck 1	Truck 2

——— 10th Lunar Cycle ———

> Flight # 4
> Lander arrives with RFC, habitat foundations

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup • Continues beneficiation of industrial power area • Gravel deposited in workyard	• C/o and startup • Unloads lander cargo • Lander takes off • Sets out RFC • Unpacks habitat foundations	• C/o and startup • Begins to spread gravel and compact the workyard	• C/o and startup • Assists in RFC emplacement • Lays above groundpower cables and does connections
		• All vehicles shutdown the lunar night	

——— 11th Lunar Cycle ———

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup • Begins beneficiation of ilmenite reactor area • Gravel deposited in the workyard • Gravel deposited in the ilemite reactor area	• C/o and startup • Sets out habitat foundations • Deposits reserved 4 hoppers over habitat foundations	• C/o and startup • Finishes spreading gravel and compacting the workyard • Spreads gravel and compacts habitat foundation area when foundations are emplaced	• C/o and startup • Assists in habitat foundation placement
		• All vehicles shutdown for the lunar night	

——— 12th Lunar Cycle ———

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup • Finishes benificiation and mining ilmenite reactor area • Continues beneficiation and mining expansion of the base • Gravel deposited on the reactor area • Gravel deposited on the straddler road	• planned down time	• Spreads gravel and compacts ilmenite reactor area • Spreads gravel and compacts straddler road	• Supports straddler 1 as required • Converts rovers to manned vehicles • planned down time
		• All vehicles shutdown for the lunar night	

Table 3-2 (Continued)

13th Lunar Cycle

Flight #5 — Lander arrives with workshop, node, primary airlock, cupola and tunnel, workshop equipment, shelter hardware, and power cables

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup	• C/o and startup	• C/o and startup	• C/o and startup
• Continues beneficiation and mining expansion of the base	• Unloads cargo	• Continues compacting the the straddler road as the gravel is deposited	• Supports unloading
• Gravel deposited on the straddler road	• Lander takes off	• Continues compacting gangue barrier as required	• Supports straddler 2, secure node, etc. on foundations
	• Node, workshop, cupola and airlock set		• Supports shelter inspection and erection
	• Begin shelter erection		

• All vehicles shutdown for the lunar night

14th Lunar Cycle

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup	• C/o and startup	• C/o and startup	• C/o and startup
• Continues beneficiation expansion of the base	• Shelter erection continues	• Continues to compact straddler road	• Supports shelter erection
• Gravel deposited on the straddler road			

• All vehicles shutdown for the lunar night

15th Lunar Cycle

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup	• C/o and startup	• C/o and startup	• C/o and startup
• Continues beneficiation and expansion of the base	• Continues shelter erection inner wall of the shelter	• Continues to compact straddler road	• Deploys and connects power cables
• Gravel deposited on the straddler road			• Helps set lights and connect power
			• Helps set light fixtures

• All vehicles shutdown for the lunar night

16th Lunar Cycle

Flight #6 — Lander arrives with habitat and airlock radiator, radiator equipment, communication equipment

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup	• C/o and startup	• C/o and startup	• C/o and startup
• Continues beneficiation and expansion of ther base	• Unloads lander		
• Gravel deposited on the straddler road	• Lander takes off	• Supports shelter erection	
	• Habitat set	• Continues to compact the straddler road	
	• Erects habitat shelter		

/

• All vehicles shutdown for the lunar night

17th Lunar Cycle

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup	• C/o and startup	• C/o and startup	• C/o and startup
• Continues beneficiation and expansion of the base (duty cycle now 40.5 sq m / hr cleared)	• Continues shelter erection Outter wall construction begins	• Continues compacting the straddler road	• Supports straddler 2
Gravel deposited on the straddler road			
Gravel deposited on the industrial power area			
Gangue deposited as shelter wall fill as available			

• All vehicles shutdown for the lunar night

18th Lunar Cycle

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup	• C/o and startup	• C/o and startup	• C/o and startup
• Planned down time	• Emplaces radiator	• Finishes compacting straddler road	• Supports radiator emplacement
	• Emplaces radiator sunshade	• Supports habitat construction as required	• Supports radiator sunshade emplacement
	• Helps emplace communications equipment as required		• Deploys communications equipment
			• Make power and communication connections
			• Cleans Habitat arrays
			• Does planned maintenance operations on straddler 1

Remote Habitat Checkout

• All vehicles shutdown for the lunar night

19th Lunar Cycle

7 th Flight — Manned Mission
- checks out habitat
- checks out workshop
- LOX processing experiments
- stay time 30 days

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup	• C/o and startup	• C/o and startup	• C/o and startup
• maintenance check	• Continues beneficiation and mining expansion of the base	• maintenance check	• Spreads gravel and compacts industral power area as required
• Exchanges miner box with straddler 2	• Gravel deposited on the industrial power area		
	• Sets down miner box at end of the lunar day		

• All vehicles shutdown for the lunar night

Table 3-2   *(Continued)*

Straddler 1	Straddler 2	Truck 1	Truck 2

20th Lunar Cycle

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup	• planned down time	• C/o and startup	• planned down time
• Attaches miner box		• Spreads gravel and compacts industrial power area as required	
• Continues beneficiation and mining extension of the base			
• Gravel deposited on the industrial power area			

• Lander takes off at the end of the previous lunar night (1 to 2, 24 hour periods into the lunar day)

• All vehicles shutdown for the lunar night

21st Lunar Cycle

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup	• Planned down time	• C/o and startup	• C/o and startup
• Continues beneficiation and mining expansion of the base		• Spreads gravel and compacts industrial power area as required	• planned down time
• Gravel deposited in the industrial power area			

• All vehicles shutdown for the lunar night

22 nd Lunar Cycle

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8 th Flight
10 solar arrays for industrial area,
5 discharge hoppers, O2 reactor
discharge cart and tracks, cables
and grounds, Base Power
conditioning unit, 2 blast deflectors,
LOX storage area spares and stores
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Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup	• C/o and startup	• C/o and startup	• C/o and startup
• Continues beneficiation and mining expansion of the base	• Unloads lander to safe distance	• Continues to spread and compact gravel on the industrial power area	• Assists in unloading lander
• Gravel deposited in the industrial power area	• Lander takes off		• Positions and anchors rails at the reactor area
	• Sorts cargo		
	• Sets out cart and rails		• Lays surface power cables and grounds
	• Sets out Base Power conditing unit		
	• Begins erecting solar arrays		

• All vehicles shutdown for the lunar night

23rd Lunar Cycle

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup	• C/o and startup	• C/o and startup	• C/o and startup
• Continues beneficiation and mining expansion of the base	• Finishes setup of the 10 industrial solar arrays	• Finishes spreading gravel and compacting industrial power area	• Connects power cables and grounds
• Gravel deposited at the industrial power area (1 hopper full)	• Sets up blast deflectors		• Assists in stockpiling spares and stores
	• Stockpiles spares and stores		
• Gravel then stockpiled			• Performs maintenance checks

• All vehicles shutdown for the lunar night

24th Lunar Cycle

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup	• Planned down time	• C/o and startup	• Planned down time
• Continues beneficiating and mining expansion of the base		• Finishes spreading gravel and compacting industrial power area	
• Stockpiles all processed material			

• All vehicles shutdown for the lunar night

25th Lunar Cycle

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9t h Flight
RFC, 1 discharge cart,
3 hoppers
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Straddler 1	Straddler 2	Truck 1	Truck 2
• Planned down time	• C/o and startup	• Planned down time	• C/o and startup
	• Unloads lander		• Lays surface power cables and grounds brought previously
	•Lander takes off		
	• Emplaces hoppers		
	• Emplaces the discharge cart		• Does power connections
	• Emplaces RFC		

• All vehicles shutdown for the lunar night

26th Lunar Cycle

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup	• Planned down time	• C/o and startup	• Planned down time
• Continues beneficiation and mining expansion of the base		• Supports straddler 1 as required	

• All vehicles shutdown for the lunar night

Table 3-2 *(Continued)*

Straddler 1	Straddler 2	Truck 1	Truck 1

———— 27th Lunar Day ————

Straddler 1	Straddler 2	Truck 1	Truck 1
• C/o and startup	• Planned down time	• C/o and startup	• Planned down time
• Continues beneficiation and mining expansion of the base		• Supports straddler 1 as required	
		• All vehicles shutdown for the lunar night	

———— 28th Lunar Day ————

10th Flight
2 Blast deflectors, spares, 3 hoppers, LOX plant lines, hydrogen gas, LOX storage tanks (2), radiators, sunshades, refrigeration units(3), valve boxes (2), LOX storage support structures

Straddler 1	Straddler 2	Truck 1	Truck 1
• C/o and startup	• C/o and startup	• C/o and startup	• C/o and startup
• Continues beneficiation and mining expansion of the base	• Unloads lander to a safe distance	• Assists straddler 1 as required	
	• Lander takes off		• Assists in construction of the the storage plant foundations
	• Erects LOX storage plant foundations		
	• Emplaces storage tanks		• Assists in emplacing the storage tanks
		• All vehicles shutdown for the lunar night	

———— 29th Lunar Cycle ————

Straddler 1	Straddler 2	Truck 1	Truck 1
• C/o and startup	• C/o and startup	• C/o and startup	• C/o and startup
• Continues beneficiation and mining expansion of the base	• Sets up radiators	• Supports straddler 1 as required	• Emplaces 1 valve box at the landing pad
	• Assists in plumbing connections at the LOX storage plant		• Starts plumbing connections at the LOX storage plant
	• Erects Blast deflectors		
		• All vehicles shutdown for the lunar night	

———— 30th Lunar Cycle ————

Straddler 1	Straddler 2	Truck 1	Truck 1
• C/o and startup	• C/o and startup	• C/o and startup	• C/o and startup
• Continues beneficiation and mining extension of the base	• Assists in LOX storage area plumbing connections as required	• Supports straddler 1 as required	• Finishes LOX storage plant plumbing connections
	• Assists in erection of the sunshade as required		• Erects the radiator sunshade
			• Connects power lines from the storage area to supply and control systems
	• Remote checkout of the LOX storage area performed		/
	• All vehicles shutdown for the lunar night		

———— 31st Lunar Cycle ————

11th Flight
Oxygen reactor #1

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup	• C/o and startup	• C/o and startup	• C/o and startup
• Continues beneficiation and mining expansion of the base	• Unloads lander to a safe distance	• Supports straddler 1 as required	
	• Lander takes off		
	• Emplaces oxygen reactor over the discharge cart rails		• Does plumbing connections from the O2 reactor to the LOX storage area
	• Loads the O2 reactor with stored ore		• Does the O2 reactor electrical connections
	• Remote checkout of the O2 reactor done		
	• All vehicles and systems shutdown for the lunar night		

———— 32nd Lunar Cycle ————

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup	• Planned down time	• C/o and startup	• Planned down time
• Continues beneficiation and mining expansion of the base		• Supports straddler 1 as required	

O2 Reactor #1

• Begins production cycle with cool down done during the next lunar night

———— 33rd Lunar Cycle ————

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup	• C/o and startup	• C/o and startup	• C/o and startup
• Continues beneficiation and mining expansion of the base	• Transports and stockpile dumps the reactor slag	• Supports Straddler 1 as required	• Opens reactor port and allows the reactor to dump slag
	• Fills O2 reactor when it is emptied		• Removes dumped slag (2 hoppers, removedone after the other) pulling the discharge cart out after each hopper
			• Inspects inside reactor and cleans it as required
	• All vehicles shutdown for the lunar night		• Seals reactor port after it has been filled with stockpiled ore

O2 Reactor #1 *

• Reactor tilts to be emptied, inspected, and cleaned

• Reactor is filled and sealed

• Reactor production cycle begins

* NOTE : The reactor dumps slag, is inspected and cleaned by the truck working off batteries and recharging off the RFC in the pre-dawn hours before lunar day

Table 3-2 (Continued)

Straddler 1	Straddler 2	Truck 1	Truck 2

━━━ 34th Lunar Cycle ━━━

> 12 th Flight
> Manned Mission
> 30 day stay time

Straddler 1	Straddler 2	Truck 1	Truck 2
• Planned down time for maintenance check	• C/o and startup • Transports and stockpile dumps the reactor slag • Fills O2 reactor when it is empted	• Planned down time	• C/o and startup • Opens reactor port and allows the reactor to dump slag • Removes dumped slag (2 hoppers, removed one after the other), pulling the discharge cart out after each hopper • Inspects inside reactor and cleans it as required • Seals reactor port after it has been filled with stockpiled ore

O2 Reactor #1

• Reactor tilts to be empted, inspected,and cleaned
• Reactor is filled and sealed
• Reactor production cycle begins

━━━ 35 th Lunar Cycle ━━━

• Lander takes off

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup • Continues beneficiation and mining expansion of the base	• C/o and startup • Transports and stockpile dumps the reactor slag • Fills O2 reactor when it is empted	• C/o and startup • Supports straddler 1 as required	• C/o and startup • Opens reactor port and allows the reactor to dump slag • Removes dumped slag (2 hoppers, removed one after the other), pulling the discharge cart out after each hopper • Inspects inside reactor and cleans it as required • Seals reactor port after it has been filled with stockpiled ore

O2 Reactor #1

• Reactor tilts to be empted, inspected,and cleaned

• Reactor is filled and sealed

• Reactor production cycle begins

━━━ 36th Lunar Cycle ━━━

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup • Continues beneficiation and mining expansion of the base	• C/o and startup • Transports and stockpile dumps the reactor slag • Fills O2 reactor when it is empted	• C/o and startup • Supports straddler 1 as required	• C/o and startup • Opens reactor port and allows the reactor to dump slag • Removes dumped slag (2 hoppers, removed one after the other), pulling the discharge cart out after each hopper • Inspects inside reactor and cleans it as required • Seals reactor port after it has been filled with stockpiled ore

O2 Reactor #1

• Reactor tilts to be empted, inspected,and cleaned

• Reactor is filled and sealed

• Reactor production cycle begins

━━━ 37th Lunar Cycle ━━━

> 13th Flight
> 11 solar arrays, LOX transfer cart, cables and grounds, 4 discharge carts

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup • Continues beneficiation and mining expansion of the base	• C/o and startup • Transports and stockpile dumps the reactor slag • Fills O2 reactor when it is empted • Unloads lander • Emplaces the discharge carts • Erects the solar arrays	• C/o and startup • Stores spare parts • Assists in solar array set up • Lays and connects cables and grounds for the arrays • Takes the LOX cart to the storage area	• C/o and startup • Opens reactor port and allows the reactor to dump slag • Removes dumped slag (2 hoppers, removed one after the other), pulling the discharge cart out after each hopper • Inspects inside reactor and cleans it as required • Seals reactor port after it has been filled with stockpiled ore

O2 Reactor #1
• Reactor tilts to be empted, inspected,and cleaned
• Reactor is filled and sealed
• Reactor production cycle begins

Table 3-2 (*Continued*)

Straddler 1	Straddler 2	Truck 1	Truck 2

38th Lunar Cycle

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup	• C/o and startup	• C/o and startup	• C/o and startup
• Continues beneficiation and mining expansion of the base	• Transports and stockpile dumps the reactor slag	• Supports straddler 1 as required	• Opens reactor port and allows the reactor to dump slag
	• Fills O2 reactor when it is empted		• Removes dumped slag (2 hoppers, removed one after the other), pulling the discharge cart out after each hopper
			• Inspects inside reactor and cleans it as required
			• Seals reactor port after it has been filled with stockpiled ore

O2 Reactor #1

• Reactor tilts to be empied, inspected,and cleaned

• Reactor is filled and sealed

• Reactor production cycle begins

39th Lunar Cycle

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup	• C/o and startup	• C/o and startup	• C/o and startup
• Continues beneficiation and mining expansion of the base	• Transports and stockpile dumps the reactor slag	• Supports straddler 1 as required	• Opens reactor port and allows the reactor to dump slag
	• Fills O2 reactor when it is empted		• Removes dumped slag (2 hoppers, remove one after the other), pulling the discharge cart out after each hopper
			• Inspects inside reactor and cleans it as required
			• Seals reactor port after it has been filled with stockpiled ore

O2 Reactor #1

• Reactor tilts to be empied, inspected,and cleaned

• Reactor is filled and sealed

• Reactor production cycle begins

/

40th Lunar Cycle

> 14th Flight
> Oxygen Reactor #2

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup	• C/o and startup	• C/o and Startup	• C/o and startup
• Continue beneficition and mining expansion of the base	• Transports and stockpile dumps the reactor #1 slag	• Connects O2 Reactor #2 electrical systems and plumbing	• Opens reactor port and allows the reactor to dump slag
	• Unloads lander		• Removes dumped slag (2 hoppers, removedone after the other) pulling the discharge cart out after each hopper
	•Lander takes off		
	• Emplaces O2 Reactor #2		• Inspects inside reactor and cleans it as required
	• Fills O2 reactor #1 when it is empted		• Seals reactor port after it has been filled with stockpiled ore
	• Fill O2 reactor # with stored ore		

O2 Reactor #1*
• Reactor tilts to be empied, inspected,and cleaned
• Reactor is filled and sealed
• Reactor production cycle begins

O2 Reactor #2
• Reactor is emplaced, the plumbing and electrical connections made and checkout done
• Reactor is filled with ore

* NOTE : The reactor s dumps slag, are inspected and cleaned by the truck working off batteries and recharging off the RFC in the pre-dawn hours before lunar day

41st Lunar Cycle

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup	• C/o and startup	• C/o and startup	• C/o and startup
• Continues beneficiation and mining expansion of the base	• Transports and stockpile dumps the reactor slag from both #1 and #2 reactors	• Opens reactor #1 port and allows the reactor to dump slag	• Opens reactor #2 port and allows the reactor to dump slag
	• Fills O2 reactors 1 and 2 when they are empted	• Removes dumped slag from reactor #1 (2 hoppers removed,one after the other) pulling the discharge cart out after each hopper	• Removes dumped slag from reactor #2 (2 hoppers, removed one after the other) pulling the discharge cart out after each hopper
		• Inspects inside reactor #1 and cleans it as required	• Inspects inside reactor #2 and cleans it as required
		• Seals reactor #1 port after it has been filled with stockpiled ore	• Seals reactor #2 port after it has been filled with stockpiled ore
		• Supports straddler 1 as required	

O2 Reactor #1
• Reactor tilts to be empied, inspected,and cleaned
• Reactor is filled and sealed
• Reactor production cycle begins

O2 Reactor #2
• Reactor tilts to be empied, inspected,and cleaned
• Reactor is filled and sealed
• Reactor production cycle begins

Table 3-2   *(Continued)*

88

Straddler 1	Straddler 2	Truck 1	Truck 2

42nd Lunar Cycle

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup	• C/o and startup	• C/o and startup	• C/o and startup
• Continues benificiation and mining expansion of the base	• Transports and stockpile dumps the reactor slag • Fills O2 reactor when it is empted	• Opens reactor #1 port and allows the reactor to dump slag • Removes dumped slag from reactor #1 (2 hoppers removed,one after the other) pulling the discharge cart out after each hopper • Inspects inside reactor #1 and cleans it as required • Seals reactor #1 port after it has been filled with stockpiled ore • Supports straddler 1 as required	• Opens reactor #2 port and allows the reactor to dump slag • Removes dumped slag from reactor #1 (2 hoppers. removed one after the other) pulling the discharge cart out after each hopper • Inspects inside reactor #2 and cleans it as required • Seals reactor #2port after it has been filled with stockpiled ore

O2 Reactor #1	O2 Reactor #1		
• Reactor tilts to be empied. inspected,and cleaned • Reactor is filled and sealed • Reactor production cycle begins	• Reactor tilts to be empied. inspected,and cleaned • Reactor is filled and sealed • Reactor production cycle begins		

44th Lunar Cycle

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup	• C/o and startup	• C/o and startup	• C/o and startup
• Continues beneficiation and mining expansion of the base	• Transports and stockpile dumps the reactor slag from both reactors • Fills O2 reactors #1 and 2 when they are empted	• Opens reactor #1 port and allows the reactor to dump slag • Removes dumped slag from reactor #1 (2 hoppers removed,one after the other) pulling the discharge cart out after each hopper • Inspects inside reactor #1 and cleans it as required • Seals reactor #1 port after it has been filled with stockpiled ore	• Opens ports on reactor s # 2 , and allows the reactor to dump slag • Removes dumped slag (2 hoppers. removed one after the other) pulling the discharge cart out after each hopper • Inspects inside of the reactor #2 and cleans itas required • Seals reactor #2 port after it has been filledwith stockpiled ore

O2 Reactor #1	O2 Reactor #1	O 2 Reactor #3	
• Reactor tilts to be empied. inspected,and cleaned • Reactor is filled and sealed • Reactor production cycle begins	• Reactor tilts to be empied. inspected,and cleaned • Reactor is filled and sealed • Reactor production cycle begins	• Reactor production cycle begins	

43rd Lunar Cycle

15th Flight
O2 Reactor #3

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup	• C/o and startup	• C/o and startup • Opens reactor #1 port and allows the reactor to dump slag	• C/o and startup
• Continues beneficiation and mining expansion of the base	• Transports and stockpile dumps the reactor slag from both reactors • Unloads lander • Lander takes off • Emplaces O2 reactor #3 • Fills both active O2 reactors when they are empted • Fill reactor #3 with stored ore after checkout	• Removes dumped slag from reactor #1 (2 hoppers removed,one after the other) pulling the discharge cart out after each hopper • Inspects inside reactor #1 and cleans it as required • Seals reactor #1 port after it has been filled with stockpiled ore • Makes plumbing and electrical connections for reactor # 3	• Opens reactor #2 port and allows the reactor to dump slag • Removes dumped slag from reactor #2 (2 hoppers. removed one after the other) pulling the discharge cart out after each hopper • Inspects inside reactor #2 and cleans it as required • Seals reactor #2 port after it has been filled with stockpiled ore

O2 Reactor #1	O2 Reactor #1	O2 Reactor #3	
• Reactor tilts to be empied. inspected,and cleaned • Reactor is filled and sealed • Reactor production cycle begins	• Reactor tilts to be empied. inspected,and cleaned • Reactor is filled and sealed • Reactor production cycle begins	• Reactor is emplaced, the plumbing and electrical connections made and checkout done • Reactor is filled with ore	

45th Lunar Cycle

Straddler 1	Straddler 2	Truck 1	Truck 2
• C/o and startup	• C/o and startup	• C/o and startup	• C/o and startup
• Continues beneficiation and mining expansion of he base	• Transports and stockpile dumps the reactor slag from all reactors • Fills all O2 reactors when they are empted	• Opens reactor #1 port and allows the reactor to dump slag • Removes dumped slag from reactor #1 (2 hoppers removed,one after the other) pulling the discharge cart out after each hopper • Inspects inside reactor #1 and cleans it as required • Seals reactor #1 port after it has been filled with stockpiled ore • Supports straddler 1 as required	• Opens ports on reactor s # 2 and #3, in turn. and allows the reactors to dump slag • Removes dumped slag (2 hoppers. removed one after the other for each reactor) pulling the discharge cart out after each hopper • Inspects inside of the reactors and cleans them as required • Seals reactor ports after they have been filled with stockpiled ore

O2 Reactor #1	O2 Reactor #2	O2 Reactor #3	
• Reactor tilts to be empied. inspected,and cleaned • Reactor is filled and sealed • Reactor production cycle begins	• Reactor tilts to be empied. inspected,and cleaned • Reactor is filled and sealed • Reactor production cycle begins	• Reactor tilts to be empied. inspected,and cleaned • Reactor is filled and sealed • Reactor production cycle begins	

Table 3-2 (Continued)

STRADDLER 1

STARTUP AND CHECKOUT
UNLOADING
MOVES TO A SAFE DISTANCE
SETS OUT HOPPERS
MINES LANDING AREA
CONTINGENCY
SHUTDOWN
STARTUP
CONTINUES TO MINE LANDING AREA
CONTINGENCY
SHUTDOWN
STARTUP
CONTINUES TO MINE LANDING AREA
MINER BOX MAINTENANCE
CONTINGENCY
SHUTDOWN

1ST FLIGHT

STRADDLER 1, MINER BOX, 5 HOPPERS

1ST LUNAR CYCLE	2ND LUNAR CYCLE	3RD LUNAR CYCLE

STRADDLER 1

STARTUP
CONTINGENCY
REMOVES CARGO
ERECTS 20kW SOLAR ARRAY
SETS OUT HOPPERS
ATTACHES MINER BOX
FINISHES MINING LANDING AREA
CONTINGENCY
SHUTDOWN
STARTUP
MINES /CLEARS HABITAT ARRAY AREA
TRUCK ROAD MINED
MINER BOX DISENGAGED
BLAST DEFLECTORS ERECTED
CONTINGENCY
SHUTDOWN
STARTUP
20 kW ARRAY MOVED
MINER BOX ATTACHED
LLOX STORAGE AREA MINED
HABITAT AREA MINED
CONTINGENCY
SHUTDOWN

TRUCK 1

DEPLOYED AND CHECKOUT
HABITAT EXCAVATED 0.5 METERS
CONTINGENCY
SHUTDOWN
STARTUP
LLOX STORAGE AREA EXCAVATED TO 0.5 METER
FILLS VIBRATING ROLLER & ATTACHES IT
SPREADS AND COMPACTS LANDER PAD & TRUCK ROAD
CONTINGENCY
SHUTDOWN
STARTUP
FINISHES LANDER PAD/ TRUCK ROAD
DISENGAGES COMPACTOR & ENGAGES BUCKET WHEEL
DIGS POWER TRENCHES AND LAYS CABLES
SPREADS & COMPACTS HAB ARRAY AREA
DISENGAGES COMPACTOR AND EXCAVATES REACTOR AREA
CONTINGENCY
SHUTDOWN

2ND FLIGHT

TRUCK 1, ADAPTER PACKAGES - TRUCK AND ROVER,
20kW SOLAR ARRAY, VIBRATING ROLLER, 5 BLAST
DEFLECTORS, BUCKET WHEEL CART, CABLES AND
PLUMBING FOR BURYING, LLOX VALVE BOX

4th LUNAR CYCLE	5th LUNAR CYCLE	6th LUNAR CYCLE

Figure 3-6   *Task schedules for the busiest activity periods show*
contingency budgets.

STRADDLER 1
STARTUP
MINES WORKYARD
CONTINGENCY
SHUTDOWN
STARTUP
FINISHES WORK YARD
MINES INDUSTRIAL POWER AREA
CONTINGENCY
SHUTDOWN
STARTUP
CONTINGENCY
SHUTDOWN

STRADDLER 2
C/O ON LANDER
UNLOAD LANDER
ERECTS 40 kW SOLAR ARRAYS
ERECTS BLAST DEFLECTORS
GRAVEL HOPPER DUMPED
CONTINGENCY
SHUTDOWN
START UP
SHUTDOWN
PLANNED DOWN TIME
STARTUP
SHUTDOWN
PLANNED DOWN TIME

TRUCK 1
STARTUP
FINISH EXCAVATING REACTOR AREA TO 0.5 METERS
DISENGAGE COMPACTOR/ENGAGE BUCKET WHEEL
CABLE TRENCHES DUG, CABLE/PIPE LAID
CONTINGENCY
SHUTDOWN
STARTUP
FINISHES TRENCHES
DISENGAGES BUCKET WHEEL, ENGAGES COMPACTOR
SPREADS GRAVEL AND COMPACTS STORAGE AREA
CONTINGENCY
SHUTDOWN
STARTUP
COMPACTS GANGUE BARRIER
SHUTDOWN
PLANNED DOWNTIME

TRUCK 2
DEPLOY & C/O
ASSISTS IN ARRAY CONNECTIONS
ASSISTS IN ERECTING BLAST DEFLECTORS
SHUTDOWN
PLANNED DOWN TIME
STARTUP
SHUTDOWN
PLANNED DOWNTIME
STARTUP
SHUTDOWN
PLANNED DOWNTIME

△
3rd FLIGHT

STRADDLER 2, TRUCK 2, 40kW SOLAR ARRAYS,
TRUCK/ROVER ADAPTER PACKAGE, TOOL CART,
4 BLAST DEFLECTORS

7th LUNAR CYCLE	8th LUNAR CYCLE	9th LUNAR CYCLE

STRADDLER 1
STARTUP AND CHECKOUT
CONTINUES MINING INDUSTRIAL POWER AREA
CONTINGENCY
SHUTDOWN
STARTUP
MINES REACTOR AREA
CONTINGENCY
SHUTDOWN
STARTUP

STRADDLER 2
STARTUP
CONTINGENCY
UNLOADS LANDER
EMPLACES HABITAT RFC
UNPACKS HABITAT FOUNDATIONS
CONTINGENCY
SHUTDOWN
STARTUP
SETS OUT HABITAT FOUNDATIONS
DUMPS RESERVED 4 HOPPERS
SHUTDOWN
FINISHES REACTOR AREA
MINING EXPANSION OF BASE
CONTINGENCY
SHUTDOWN

TRUCK 1
STARTUP
GRAVELS/COMPACTS WORKYARD
CONTINGENCY
SHUTDOWN
STARTUP
FINISHES WORKYARD
PLANNED DOWN TIME
GRAVELS/COMPACTS HAB. FOUNDATIONS
CONTINGENCY
STARTUP
SHUTDOWN
CONTINGENCY
SHUTDOWN

TRUCK 2
STARTUP
CONTINGENCY
ASSIST IN HAB. RFC EMPLACEMENT
LAYS CABLES
SHUTDOWN
STARTUP
FINISHES COMPACTING THE STRADDLER ROAD
ASSISTS IN HAB FOUNDATIONS
SHUTDOWN
STARTUP
COMPACTS REACTOR AREA
CONTINGENCY
SHUTDOWN
PLANNED DOWN TIME
STARTUP
CONVERTS ROVERS TO MANNED OPS
SHUTDOWN
CONTINGENCY

△ 4TH FLIGHT
RFC, HABITAT FOUNDATIONS

10TH LUNAR CYCLE	11TH LUNAR CYCLE	12TH LUNAR CYCLE

(NOTE: AVAILABILITY OF GRAVEL LIMITS RATE OF COMPACTION)

Figure 3-6 *(Continued)*

Figure 3-6 (Continued)

Figure 3-6   (Continued)

functioning of the habitat-workshop complex, and to perform final qualifying investigations with pilot oxygen-reactor components and soil chemistry. In addition, the crew will have the opportunity to observe mining operations and review, "eyeballs-on", the performance of robotic maintenance activity. They will be capable of intervening in these operations as necessary, or performing additional checks and corrections, fine-tuning the robotic operations. The habitat system will be usable as a fully functional IVA control center for supervision and teleoperation. Finally, they will use the second half of their stay (during the lunar night), to perform IVA repair work on faulty base equipment.

The actual industrial site buildup takes four dedicated flights (one year) before initial plant startup. Production begins when the liquefaction/storage depot and the first oxygen reactor can be brought on line, to test the end-to-end system. The second crew visit occurs at this point, as the 12th flight (34th lunar cycle AFL). This visit will verify the system function, and allow adjustments and repairs as required. Additional ISRU tests (recovering iron from reactor slag, sintering construction materials, producing glass fiber or performing other experiments) may be conducted at this time. Again, monitoring nominal robotic

functions, gaining experience with in situ teleoperation, and performing nighttime component repairs will round out crew activities.

FINDINGS - We found that the operations were mainly constrained by frequency of lunar transport flights, rather than by capacities of the robotic equipment. That is, despite orderly manifesting, the periodic yet sparse arrival of necessary equipment paced the buildup schedule, which we measure AFL (after the first cargo landing). Even the optimistic flight rate groundruled into the scenario stretched the total buildup time to four years. **The time between first landing and habitability is 1.5 yr, and the time to first oxygen production is 2.75 yr AFL. Full production of 100 t/yr LLOX is attained at 3.75 yr AFL.** As noted earlier, limiting these lag times enhances the economic viability of the enterprise.

Only at the beginning of the buildup schedule, when activity is paced by specific site preparation milestones, are the robots used almost full-time. During this period, the schedule is most sensitive to unplanned interruptions, although the overall program is probably most tolerant of delays while the base is not yet manned. Later, as the base industrial equipment arrives and is set up, checked out, and brought on line, extensive downtime results from the infrequency of lunar cargo delivery. The planned downtime comprises a contingency buffer, permitting machine overhauls and freeing up vehicles for other, investigative purposes. An important conclusion from our schedule analysis is that when building a small lunar base, **4 flights/yr is an appropriate maximum rate at the very beginning, but more frequent traffic becomes desirable within the first two years.** Since our oxygen production capacity was designed to support only 4 flights/yr, a most efficient combination of production and traffic rates remains inconclusive.

We also found, as noted above, that the amount of work which must be completed is controlled early on by site preparation. In particular, **even a simple paving scheme can easily dominate other constraints**; designing site preparation activity to be commensurate with later production activity provides a strong incentive to minimize the sitework performed. Our base site plan represents the iterated result of direct efforts to reduce the paved area, as does the 5 cm paving thickness we selected. The most tempting way to accommodate more sophisticated sitework infrastructure is to relax the goal of early habitation and oxygen production. The cost of that relaxation is however high; more

extensive facilities will be a natural, but later, outgrowth of a modest base whose purpose is to demonstrate the critical capabilities.

The result that substantial amounts of lunar resources can be regularly and productively incorporated into an ongoing lunar transportation system within just 4 yr of landing the first equipment on the Moon, is novel. The potential benefit for space exploration programs of such timely return on the ISRU investment warrants belaboring explicitly two corollary conclusions. **First, the short lag time is a direct function of an aggressive, but achievable, cargo flight rate.** If only two landings are accomplished per year, or if half of all flights are crew-carrying instead of cargo-delivering, then 8 yr will separate the first landing from full oxygen production. **Second, the short lag time is a direct function of eschewing constant, on-site crew involvement.** Insisting that crew must be present to accomplish major buildup tasks automatically limits base buildup to the exploration program's ability to keep human crews on the lunar surface. If the buildup can instead be reliably accomplished under supervisory control from Earth, punctuated by short, on-site verification sorties, a much more rapid and safe buildup can occur.

3.2   DELIVERY MANIFESTING

An integral part of the end-to-end reference scenario is the timely arrival of equipment needed to build up the lunar base. Two primary constraints are flight capacity (baselined as 30 t of cargo per landing) and flight rate (baselined as 4/yr). Important considerations are: bringing equipment in the right order for the staged, orderly base buildup described in section 3.1; insuring within that overall framework that individual robots arrive in time to support each other and so that the intervals between cargo deliveries are effectively utilized; including a "packaging" mass allowance to account for the complication that some payloads consist of many small pieces; distributing a mass budget for spare parts among the lander flights so that an onsite spares stockpile grows along with the base. Program contingencies may force re-manifesting, even close to a launch. For example, the need for a critical spare part might reshuffle the manifest, as would the need to

alter a piece of equipment based on fresh in situ experience, and thus delay its launch. The manifest we developed serves as a reference for mass accounting (and in fact is a convenient weight listing of all the base systems: primary, mobile and utility elements, and spares). Mass growth margins have been embedded in all equipment masses as listed.

Figure 3-7 presents the reference delivery manifests for all 15 flights required by our reference scenario. These are mass-based only (detailed volume-packaging concepts for each flight were not developed). Details of the ETO manifesting, transfer to LLO, and

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Flight 0 (direct Atlas - Centaur mission)

- Rovers #1 & #2
- Site survey equipment

Flight 1

• Straddler #1	12.5
• Miner	10
• 5 hoppers	6.0
• Packaging	1.0
TOTAL	29.5 t

Flight 2

• Truck #1	6
• Truck boom tools	4
• Fluid & power lines for burying	1.9
• LLOX terminal	0.1
• 3 hoppers	3.6
• 1 20 kWe PV unit	1.3
• Vibrating compactor	1
• Bucket-wheel excavator trailer	0.8
• 4 debris shields	3.2
• Spares	6.5
• Packaging	1.5
TOTAL	29.9 t

Flight 3

• Straddler #2	12.5
• Truck #2	6
• Truck boom tools	4
• 2 PV units	2.5
• Utility trailer	0.8
• 4 debris shields	3.2
• Packaging	1.0
TOTAL	30.0 t

Flight 4

• RFC module (for habitat system)	25.4
• Habitat shelter foundation materials	4
• Packaging	0.6
TOTAL	30.0 t

Flight 5

• Workshop module, node & primary airlock	17.3
• Cupola & tunnel	2.2
• Shelter structure	7.5
• Power cables	2.0
• Packaging	1.0
TOTAL	30.0 t

Flight 6

• Main habitat module & secondary airlock	20.0
• Shelter structure	3.0
• Communication equipment	0.5
• Radiator & sunshade	0.7
• Local lights	1.5
• Spares & stores	3.0
• Packaging	1.3
TOTAL	30.0 t

Flight 7 (crew - carrying mission)

- Stay time 30 d
- Verifies habitability
- Monitors robots
- Qualifies oxygen process

Figure 3-7   *The delivery manifest is also a weights statement for the lunar base.*

transfer activities between space vehicles were not considered in this analysis. Those details would of course be a vital part of an overall lunar base logistics and operations study, but were beyond the scope of this work. Two of the flights are crew-carrying, and thus bring no cargo. A summary of the nominal delivery scheme follows:

Flight 8

• 10 PV units	12.5
• Slag - hopper cart and rails	3.5
• 5 hoppers	6.0
• Power and ground cables	1.0
• Power switching substation	0.3
• 2 debris shields	1.6
• Spares	3.0
• Packaging	1.8
TOTAL	**29.7 t**

Flight 12 (crew - carrying mission)

- Stay time 30 d
- Verify LLOX production
- Investigate other ISRU
- Detailed repairs as needed

Flight 9

• RFC Module (for industrial plant)	25.4
• Slag - hopper cart	1.0
• 3 hoppers	3.6
• Packaging	1.0
TOTAL	**30.0 t**

Flight 13

• 11 PV units	13.8
• Lander conditioning trailer	1.0
• Power & grounding cables	0.5
• 3 hoppers	3.6
• 1 spare slag - hopper cart	1.0
• Spares	9.0
• Packaging	1.0
TOTAL	**29.9 t**

Flight 10

• LLOX depot tanks	1.0
• Depot support structures	5.5
• Depot refrigeration units	0.5
• Depot radiator, sunshades & platform	1.3
• Depot plumbing	10.0
• 3 hoppers	3.6
• 2 debris shields	1.6
• 2 LLOX terminals (future growth)	0.2
• Hydrogen make-up gas reserve	0.5
• Spares	3.0
• Packaging	2.0
TOTAL	**29.3 t**

Flight 14

• Oxygen reactor #2	30.0 t

Flight 15

• Oxygen reactor #3	30.0 t

Flight 11

• Oxygen reactor #1	30.0 t

Total equipment mass	**388 t**
Spares provisioned	**24.5 t**

Figure 3-7 (*Continued*)

"Flight #0" (a small, dedicated flight) brings both rovers with equipment to survey, map and mark the site prior to heavy cargo delivery. The rovers self-deploy from their expendable lander.

Flight #1 brings straddler #1 and the miner, allowing immediate site clearing and material beneficiation for paving gravel.

Flights #2 & 3 bring straddler #2, both trucks, all the equipment necessary for completing excavation and assembly tasks, most of the landing pad utilities, and PV arrays.

Flight #4 brings foundation materials and an RFC storage module for the habitat system.

Flights #5 & 6 bring the habitat and shelter hardware, allowing completion of the habitat system.

Flight #7 is the manned mission to inspect base buildup so far and verify habitability.

Flights #8, 9 and 10 bring industrial utilities and the LLOX depot components, so that all facilities are in place before the oxygen reactors arrive.

Flight #11 brings oxygen reactor #1, allowing pilot production and storage of LLOX. Flight #12 is the manned mission to monitor the production process.

Flight #13 brings the balance of utilities required for LLOX production and usage.

Flights #14 & 15 bring oxygen reactors #2 & 3.

After the 15th flight, the base is fully outfitted for human visits and 100 t/yr production of LLOX. Subsequent delivery flights would be for base growth, and have not been manifested by this study. Furthermore, we have not investigated manifesting for the return of samples, equipment or products to Earth from the lunar base.

3.3 ROBOTIC TECHNOLOGY AND MACHINE CONTROL

MANIPULATORS - Manipulators are an essential component of the three mobile robot concepts presented here. They are used to perform positioning, assembly, maintenance, and sampling activities with varying dexterity, precision, reach, and strength requirements. These diverse requirements imply at least two separate manipulator configurations: one for the straddler and one for the truck and rover.

The design of a manipulator (joint configuration, mechanical system, and dimensions) is bracketed by often conflicting performance requirements, operating environment features, and the deployment method provided by the host vehicle. The straddler manipulators are required to reach relatively long distances, maneuver massive and bulky payloads, sometimes work in coordination, and perform fastening and maintenance activities. These last two requirements impose perhaps the largest, most costly design constraints: long-distance dexterity and precision imply a stiffness that is achievable only through large, massive sections and elaborate control methods. Therefore, as is often done in terrestrial applications, the requisite dexterity and precision should be relinquished to a lesser, specialized actor — in this case the end-of-boom manipulator pair on the high-reach truck. The link dimensions and drive components comprising the straddler manipulators can therefore be optimized to provide the required payload, reach and modest stiffness, with minimum mass and cross-section. Both straddler manipulators are identical, to minimize spare parts inventory; one manipulator can be cannibalized to repair the other if necessary.

The high-reach truck manipulator's configuration is dominated by the requirements for precision, dexterity, and work in confined spaces; reach is not an overriding concern since the gross motions needed to get to the work site are provided by the deployment boom and truck base. Dexterity and precision are not difficult to achieve (given limited reach requirements), but the need to work in confined spaces is a significant design constraint. The manipulator mechanism must be trim and compact, to pass through or near constrictions, and motions must be compact (minimal swept volumes) yet able to reach around complex shapes. Extensible members are often optimal for providing low swept volumes ("point and shoot" motions) and concentric torque-tube drives can provide several axes of motion at virtually the same point, but both these motion scenarios require greater mechanism and therefore increased supporting structures and mass penalty.

Robot components for some applications benefit greatly from commonality and modularity. Applying principles of commonality and modularity to fittings and connectors, testing and repair procedures, and protocols can maximize the efficiency of logistics. Modularity and commonality of complete joint components is conceptually beneficial (particularly to maintenance scenarios), but the mass penalty associated with using excessively powered actuators, and the resulting increase in link dimensions to support them, must be traded against the logistical simplicity of a smaller kit of parts. Modularity can translate the problem of fitting tools to a particular job from the hardware domain to the control, or software, domain. For example, reconfigurable joints are potentially beneficial by facilitating immediate, functional manipulator refits (or cannibalization of other manipulators) to customize performance capabilities for unanticipated tasks or in response to contingencies. (A reconfigurable arm consists of common joints, simple inter-joint links with embedded processors, a serial bus threading through each link, and a sophisticated control system which adjusts its data interpretation and signal generation based on the present configuration of joints.) The system flexibility afforded by reconfigurable technology may prove enhancing for some lunar operations, where the range of dexterity required for maintenance and changeout operations will realistically grow to be quite broad. However, reconfigurability need not be essential for the early lunar base, since the accommodation of most task situations can be designed into the base equipment beforehand; optimization of manipulator dimensions and effectiveness usually occurs through configuration specificity.

For each of the manipulators discussed, rotary direct-drive is a likely candidate method of actuating all joints. Direct-drive eliminates the need for gearing and coupling mechanisms and therefore minimizes the length, mass, and inertia of manipulator links.

SENSORS - Sensors for robotic systems continue to be developed rapidly, with some recent advances showing particular promise for lunar application. In particular, fiberoptic sensors embedded directly in mechanical components can provide required information on strain, position, acceleration, temperature, and magnetic and electrical fields. This technology has advanced dramatically in the last five years, leading to robust, simple, reliable and extremely long-lived transducers with great precision. The "smart part" allows more complete performance monitoring and fault diagnosis.

We have already discussed the use of positional beacons around the base, for navigational and manipulation purposes. Devices requiring such data (mobile robots and manipulators) must have antennas to detect the EM beacon broadcasts. Electromagnetically, the base will appear as a set of overlapping spherical-coordinate systems, most fixed but some moving. Processors interpreting such data must be able to translate among the local coordinate frames, enabling tools and robots to be positioned accurately anywhere in the base.

Small, fixed-head, charge-coupled device (CCD) cameras with fisheye lenses can provide hemispherical video coverage which, though difficult for humans to interpret, is adequate for robotic operations and avoids the complications of mechanical pan-and-tilt mechanisms. The images can be deconvolved computationally for more conventional presentation to human operators when desirable. Fisheye CCD "eyes" can be mounted on fixed base elements, mobile robots, EMUs, manipulators and even end effectors, to provide coverage-on-demand of local conditions, subject to practical bandwidth limitations of the base controller. Efforts to widen the acceptable dynamic range for CCDs are underway.

Scanning laser rangers yield distance-driven information extremely useful to machines and humans alike for manipulation, and more useful generally than video for navigation. Especially in the high-contrast (daytime) or completely dark (nighttime or deeply shadowed) work areas around a lunar base, the type of data generated by these increasingly compact and robust devices will prove essential. All our mobile robot concepts presume such sensors. Non-imaging laser scanners are also required for reading part identification tags, necessary for proper inventory management, part selection and task completion.

CONTROL - Robot control for lunar facility operation will be different from control for other possible space applications like surface exploration or satellite repair. The simultaneous control of many separate elements, engaged both individually and teamed in distinct activities, will be required. However, constructed facilities will be specifically designed for robotic deployment, operation and maintenance in the particular conditions expected on the Moon. Hence control can take fullest advantage of pre-knowledge of intended actions and outcomes. The Moon has sufficient gravity to aid vertical alignments, to stabilize part placements, and to overcome certain mechanical concerns of robot

hardware performance in microgravity applications. The Moon is close enough to facilitate both direct and relayed communications subject to only a few seconds of loop delay, and also to deliver payloads and power sources quite sufficient for the construction challenge. Payload, power, telemetry and flight time limitations are disadvantages that attend Mars missions (section 4).

The Moon's accessibility to crews opens the opportunity for hands-on control by operators that are in near proximity or actually aboard the robotic equipment, commanding their actions through hard controls. Automated task control can take fullest advantage of these physical circumstances and resources. Teleoperation is possible and appropriate as a primary or backup control mode for tasks of opportunity, and to intervene in the face of contingencies and other unforeseen events. Robot safeguards, reflexes and scene registration are appropriate as onboard functions to support and complement both teleoperated and automatically planned operations. The mixed mode of task control which we propose as appropriate for lunar operations robots is explained in this section.

The key requirements for controlling robotic operations for a crew-supporting, industrial base on the Moon are:

1)   To perform tasks safely, so as not to risk human health, equipment integrity, or program success.

2)   To perform tasks simultaneously, so that the many operations required for base functioning can occur in parallel and without interference.

3)   To perform tasks efficiently, so as not to burden human crews with repetitive or tedious activity.

4)   To perform tasks transparently, so that human crews can at any time interrupt, take over, redirect or redesign the task activity.

In developing a control concept for the lunar base, we avoided solutions that invoke "magic" (software technologies that might be invented in the future). We developed a modular and hierarchical approach, which facilitates machine autonomy while still

preserving human command entry points at all levels. In the remainder of this section, we examine two facets of the lunar robot control problem: a hierarchical **control architecture** which can effectively integrate human and machine skills; and a **computational architecture** to implement that control scheme.

SCENARIO - To key an extended discussion of A & R control, and convey the capabilities of control appropriate for manned and unmanned operations at a lunar base, we use the following simple, specific scenario: robotic deployment of a solar PV unit. The work is performed by a straddler. In the scenario, work has already progressed to: carry the folded solar array to its site; position and suspend the array; and while the unit is suspended, unfold the solar panels and the leg tripods which will support the unit above the ground. The next subtask is to anchor a leg to the ground by emplacing an anchor, the task that we detail here.

To anchor a leg, it is necessary to acquire an anchor, thread it through the pad and auger it into the regolith. To acquire the anchor, it is necessary to plan a sensor view, acquire and process a sensed image, determine how to grip the anchor, and then to move it. To auger the anchor to the ground, the robot aligns the anchor to an anchor pad hole, and thrusts and twists the anchor in a manner akin to power-driving a screw. The task invokes a preprogrammed construction script that has decomposed the assignment into subtasks such as data acquisition, navigation, manipulation, and (of particular interest in this work) assembly. The assembly subtask is itself decomposed into elemental actions such as sensor processing, part-grasping and motion commands that sequence and execute the physical work. We refer often to details of this simple construction task in the following discussion, as it helps make real the abstract concepts.

MULTI-TIERED CONTROL ARCHITECTURE - Accomplishing emplacement, construction, operations and maintenance tasks for a manned lunar base, using a robust mixture of A & R and crew activity, requires a hierarchical control architecture (Figure 3-8). This flexible control scheme fundamentally incorporates two critical features. First, it gives over as much control to the machines as is possible, practical and safe. Second, it preserves the opportunity for human operators (whether Earth-based, space-based, or onsite) to inject control at any level into the nominally automated system.

Its control layers presume **onboard functionality**, and proceed up from **teleoperation** through **supervisory control** to **automated task control**.

Innate capability for sensing and acting, at least for existence and safeguard, must reside onboard an unmanned construction machine. Innate onboard functionality operates at millisecond rates, in the absence of external command to support power, telemetry, robot infrastructure and provide safeguards. Beyond this, innate functionality (like image processing and motion controllers) provides the physical building blocks and behaviors (acquiring scene data and executing actions) essential for robots to act in control regimes beyond those relying on unenhanced teleoperators.
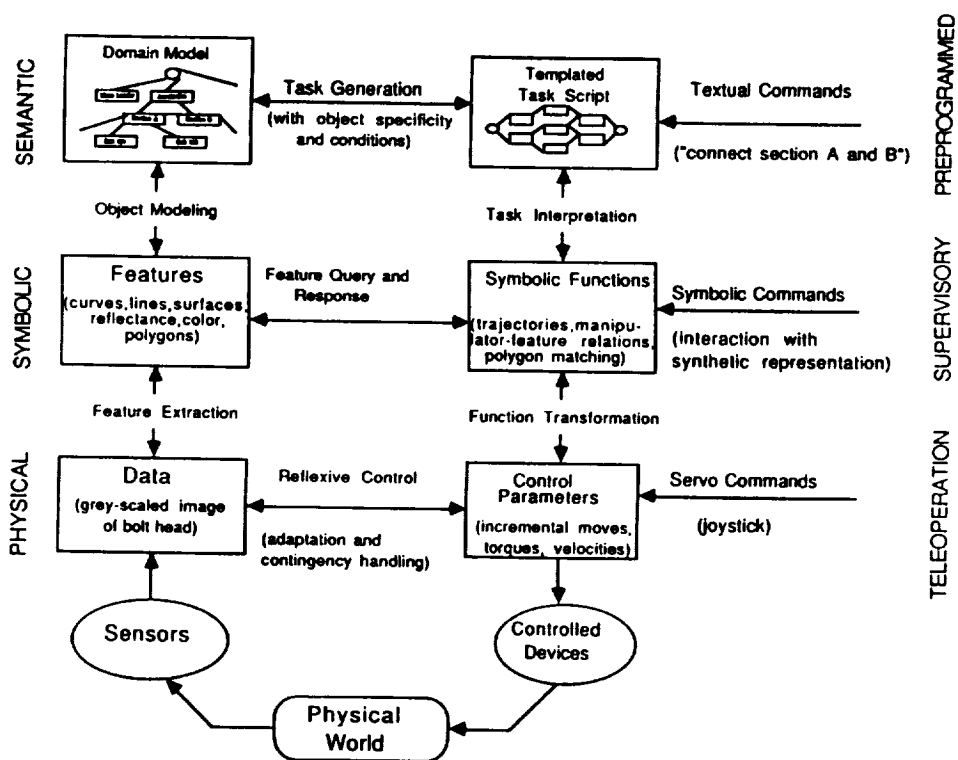
Figure 3-8   *Multi-tiered control architecture integrates machine autonomy and human control.*

Thus the lowest level in Figure 3-8 is device control primitives, such as "move a specified distance and direction" and "rotate the anchor wrench". The operator can either engage the entire primitive, or engage it by modules, such as "engage the anchor head", "apply torque x", and so forth. At this level, feedback loops are mainly internal to the robot (speeds, torques, angles), with processing located in the tool itself and operating at millisecond rates. Feedback from the external environment consists of fundamental

quantities, like "strain". Human control at this level is teleoperated, for which sensor data are processed by the operator. Teleoperation is the control of robot action by a human operator during task execution, where robot and scene data are displayed to the operator for interpretation, and where operator commands are conveyed to the robot for execution. Indirect-view data takes the form of audiovisual display, synthetic overlays and computed symbols like icons and text. The operator examines the realtime situation, decides how to respond, and issues direct machine instructions, which are then executed subject to the machine's reflexive safeguards. (These "onboard functionality" safeguards, intrinsic to the machines, also prevent accidents involving conflicting tasks or equipment during parallel operations.) Operator commands can take the form of language, such as "fetch an anchor"; symbolic actions such as moving a graphic icon on an interactive screen; or gestures, as conveyed through conventional joysticks. Teleoperation might be invoked to remove a blockage or re-position a leg if it were discovered that a rock prevented placement of a leg anchor.

When it is possible for astronauts to be in line-of-sight proximity, or physically aboard operations equipment, a preferred mode of operational control is hands-on, providing the most direct coupling of gestures to actions. However, the costs and constraints of working EVA, the difficulty of getting preferred scene views, and the tedium and difficulty of teleoperation for some tasks, all diminish the desirability of hands-on control, even when it is possible as an option. Nevertheless, a hands-on control mode introduces only a minimal additional cost, and yet a high payoff, for most robotic systems, and is invaluable for occasions such as robot setup, troubleshooting and maintenance.

Alternatively, and more efficiently, the operator can engage the next higher, "supervisory" level, where simple sequences of primitives constitute unambiguous operations: "locate anchor xyz; install it and confirm proper installation". Supervisory control is a tactical operations mode which mediates between automatic behavior and direct human control. Commands are issued symbolically ("screw in the anchor") rather than directly (as with teleoperation), and decomposed by the machine into the specific motor commands necessary to accomplish the task. Detailed planning of the motor commands, their sequencing, execution and verification are left to the machine. The robot generates feedback through feature extraction of raw sensor data. It must determine its location relative to target objects, and it must perform positive part identification, for example by bar-codes. Data provided to the human supervisor are symbolic (modeled representations

of objects, for example) rather than raw physical (like video, although the supervisor may call for such data as desirable). The supervisor has the benefit of feedback displayed in a summary form, and can issue commands for well-characterized tasks at a non-tedious level. The supervisor can at any time enter the control architecture at deeper levels, to examine raw sensor data and execute tasks directly through teleoperation.

Internal processing at the supervisory level is somewhat slower; the loop is closed at rates on the order of seconds. This means that supervisors can be located either onboard, close by, inside the base habitat system, in orbit, or even on Earth (subject to an inescapable loop delay of several seconds). Quick response to contingencies is thus possible in practical realtime. Offloading the explicit, low-level details from human crews also enables them to supervise more effectively the whole suite of mobile robots and operations equipment which work simultaneously around the base. Supervisory control appears to be a greatly enabling technique for robotic operations at a lunar base, requiring primarily well-characterized workpieces, a predictable environment, and a modicum of onboard sensor and command processing. Overall safety and efficiency of task execution are enhanced, because exclusion rules, reflexes and details are offloaded from the human. Supervisory control does not require the machine to model ("understand") an entire system or operations sequence. Such strategic planning and execution activity would require full automated task control, represented by the top level of the multi-tiered control architecture.

AUTOMATED TASK CONTROL - The next possible level involves automated task control and planning, as in the case where a command is to "unload the habitat and emplace it in the pre-planned location". On this level, several courses of action are possible, and the robots must identify feasible paths through the network of possible sequences that reach the end objective, selecting an efficient one. At this level, the robotic system could justifiably be said to "understand" substantially both a model and the reality of its work environment. Task generation occurs on the order of minutes; processing can occur remotely, even on Earth. Human intervention consists of preprogramming or changing the script template rules. Such automated task control proffers the greatest potential to avoid operations conflicts smoothly, by scheduling task activities properly, allocating resources efficiently, and tracking real-time performance conscientiously.

Pre-knowledge, invaluable to any robot process, is provided to the robotic construction activity in the form of a **domain model**, which details the parts and facility to

be built, and a **task model**, which details the sequences, means and actions for building. These are the essential inputs to automated task control as advocated here. Automated task control operates on these representations to schedule, execute, monitor and control the flow of physical actions by operators or robot agents that perform the construction tasks.

The domain model is a database of all components and assemblies that comprise the constructed facility. The model incorporates three forms of description essential to task automation (Figure 3-9): semantic, geometric, and physical. The highest, **semantic level** of a domain model is object-oriented, containing descriptions of components (what each part is and does), and their interconnecting relationships with other objects and attributes. The mechanical, power and signal connectivities amongst panels and tripods are made explicit at this level. The **geometric** model is the symbolic spatial description of the facility in the form of constructive geometry, including shape, texture and color. This three-dimensional representation identifies the location of elements such as surfaces, connections, grip-points and markers. The geometric model provides a structure whose contents are manipulable and configurable in formats used by planning, perception and actuation subsystems. The lowest level of modeling is the **physical representation** of data as viewed by a sensor, such as data fields of color, intensity and range (how a part appears from a given perspective through a given sensor under given conditions). The representation of sensory data is dependent on unique combinations of scene content, sensor attributes, sensor perspective, and environmental conditions such as lighting. Thus it is common to construct synthetic data images from models on an as-needed basis. A domain model describes a built facility, like the solar array of our example, and the functional relationships of its parts, in the detail that is needed to support robotic construction, operation and maintenance. A domain object such as our example solar array is comprised of deployable parts like panels, tripods and anchors, as well as attachments such as cabling, and detachable parts like sensors and tracking motors.

The task model (Figure 3-10) is a hierarchical network representation of a task that incorporates more than the chain of steps to sequence a series of actions. An ideal task model can be used to schedule, explain sequences, generate error recovery plans, and kill off earlier plans rendered inoperable by contingencies. Network nodes in a complete task model can be goals, commands or monitors, all essential to robust task control.

```
                        ┌─────────────┐
                        │ Solar Array │
                        └─────────────┘
    ┌──────┬──────┬──────┬──────┬──────────┬──────────┐  ...
┌────────┐┌────────┐┌────────┐┌───────┐┌─────────┐┌─────────┐
│  Top   ││ Middle ││ Bottom ││ Pivot ││Tripod A ││Tripod B │
│ Panel  ││ Panel  ││ Panel  ││ Axle  ││         ││         │
└────────┘└────────┘└────────┘└───────┘└─────────┘└─────────┘
```

Figure tree:

- Solar Array
  - Top Panel ...
  - Middle Panel ...
  - Bottom Panel ...
  - Pivot Axle
  - Tripod A
  - Tripod B
    - Leg A
      - Tripod/Panel Attachment
      - Strut
      - Ground Anchor Pad
      - Anchor
    - Leg B ...
    - Leg C ...

Object Model:

Semantics
- Object identifier: anchor pad
- Mechanical connections to other objects: tripod leg, ground, anchor
- Power/signal connections: none
- Functional Description:

Geometry & Attributes
- Geometric Primitives (circles, rectangles, etc.)
- Dimensions
- Connection Details
- Marker Locations
- Reflectance, texture, color, etc.

dia = d

Sensor Data
Template for each sensor type including:
- View Point
- Illumination
- Data point 1
- Data point 2
- .....

Figure 3-9   *The domain model describes a built facility.*

An exciting, enhancing functionality (currently emerging from research to application) for operations robots is vision-guided manipulation: the ability to sense, interpret and act on a physical detail of a work scene. In the context of our illustrative scenario, vision-guided manipulation could emplace or assist in the placement of an anchor that pins the leg of our solar array structure to the lunar regolith. Vision-guided manipulation can take a command such as "position anchor over lug hole", and interpret that command to drive the sensing, motion planning and control necessary for execution,
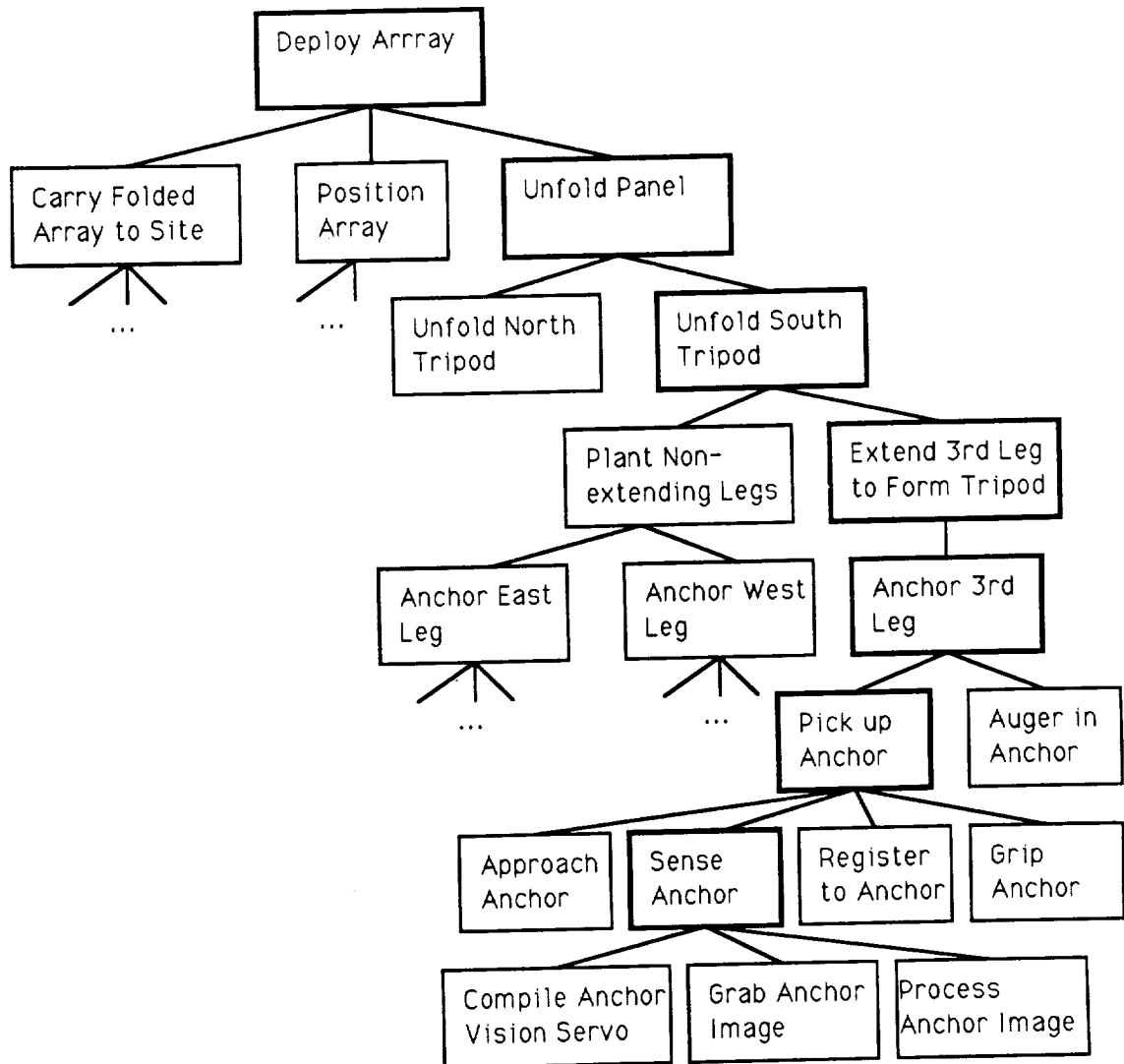
Figure 3-10 *The task model allows generation of activity scripts.*

simulation or operator advice. Through the task model it is possible to parse the example command into the domain objects (anchor and anchor hole), and to establish the intended relationship between them and the intended action, position. Through the domain model it is possible to access the intended connection of leg, anchor pad, anchor and ground, to access the geometry of each, and to construct the intended relationship of these components geometrically.

COMPUTATIONAL ARCHITECTURE - Automated task control is the orchestration of robot, sensor, site and operator resources to achieve operations goals. Task control puts the multi-tiered architecture into action. Task control is best thought of as an executive function, akin to a computer operating system that prioritizes and schedules agendas, queries for data, calls for plans, and invokes actions. Task control operates on the domain model and task-trees, with robot and operator actions, to manage implementation of the objectives. To perform productive work, task control must schedule and initiate actions, impose temporal and resource constraints, monitor performance, handle exceptions, and log events. The form of the task control architecture is software that layers onto, and is embedded into, all the functional modules, devices and data servers of the robot system.

The nature and significance of task control are evident (witness the proliferation of architecture concepts: NASREM, subsumption, blackboarding, whiteboarding), but there is little implementation and less calibration of task controllers aboard implemented robots. There is, however, current university work on Task Control Architectures (TCAs). Because of the deliberate, intentional nature of base operation tasks, and the magnitude and diversity of processing needed to execute them, we advocate control that is centralized and data processing that is distributed (Figure 3-11). A task architecture controller is an appropriate, reasoned approach to the requisite task control.

A TCA controller reasons about resource usage and contention, and can prioritize decisions. TCA control should incorporate explicit representations of task trees and scheduling constraints, and select monitored conditions. A TCA can be envisioned as layered shells of capability: communication, behavior, resource, task management, temporal constraint, monitoring, error handling, and user interaction. The inner layers are essential to the function of any system, and the outer layers represent added, elective, capabilities.

The **communication layer** connects distributed processes of the operations system. Message passing is through a central router, transparent to the system programmer. The content of messages constitutes the **behavior layer**. Query messages call for sensed data from the internal and external environment. Goal messages expand abstract, symbolic goals such as "anchor leg of solar array" into executable subgoals such as "fetch anchor", "position anchor" and "drive anchor". Command messages initiate physical actions. Constraint messages operate on the internal environment to generate advice and predictions.
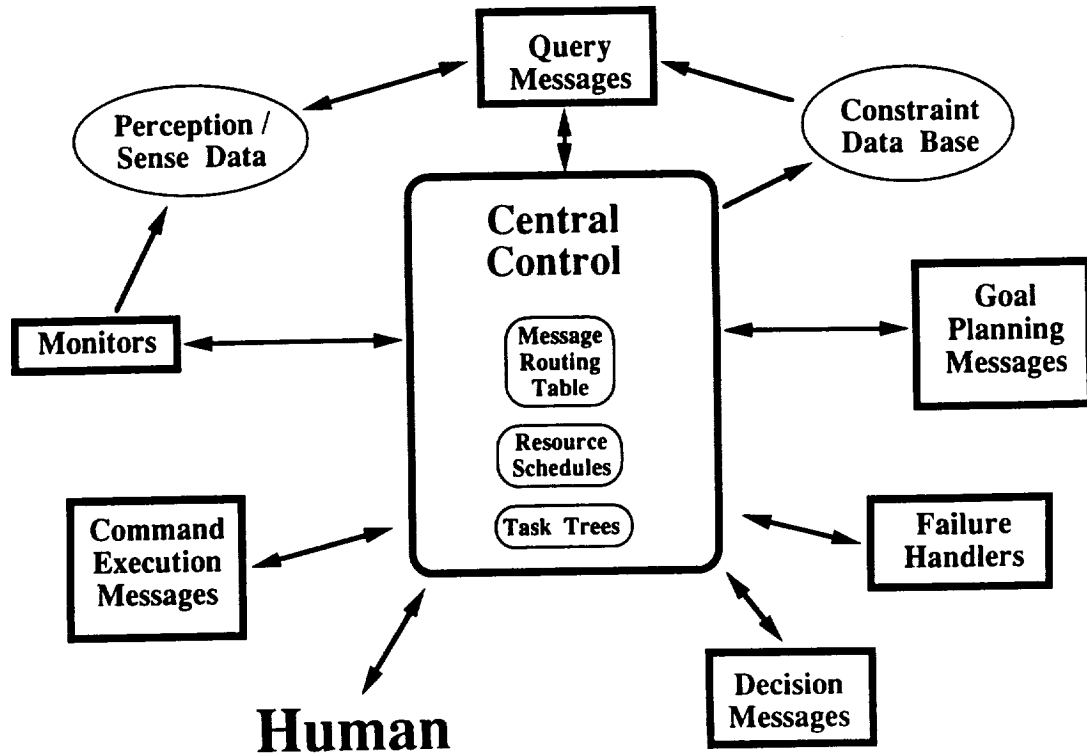
Figure 3-11 Central control of distributed processing modules is appropriate for complex task environments.

The **resource layer** reserves and synchronizes physical and computational resources of the operations system and resolves contentions. The **task management layer** operates on a hierarchical representation of the task (a network of goals and subgoals to achieve an objective) and temporally orders subgoals (scheduling), kills network subtrees when contingencies arise (error recovery), and traces the tree for an explanation of events and error recovery response. The **temporal constraint layer** enforces precedence in time and allows for setup time, achievement time for action, and a planning interval in the case of goal-setting. The **monitor layer** tracks the status of external or internal events. The **error layer** is triggered by a monitor that is tracking for error. It formulates a recovery decision using failure handlers and task-tree manipulation, then issues goal and command messages to effect recovery. Finally, the **user interaction layer** has utilities to add goals, alter resource allocation decisions, and change temporal constraints. The robot can use this interaction layer to describe the current task-tree, explain decisions, and ask for help. An ancillary but crucial benefit is the automatic generation of a detailed log of which actions (and outcomes) actually take place. This provides an invaluable data base for quality control and continuous process improvement. Event logging and automated record-keeping are straightforward outcomes of the TCA.

Nowhere in this outline of the machine control methodologies needed to operate lunar base operations robots have we invoked the chameleonic phrase "artificial intelligence" (AI). A fourth, higher control level of the multi-tiered architecture (but one not required for our lunar A & R operations) would involve true machine cognition. We claim that such sophistication qualifies as AI, whereas the lower, baselined levels do not. We draw this distinction to make the point that the software architecture outlined here is known to be tractable for object domains whose detailed characteristics are known. Whether or not that makes the machines intelligent is irrelevant, and we prefer to avoid clouding the issue of accessible lunar operations technology with vague nomenclature. (The capabilities of the engine monitoring and control systems in modern automobiles would have qualified as AI back in 1960, although in 1989 they are so standard as to be expected.) Given a well-constrained environment (a navigable lunar base) and well-characterized tools and parts, the three-tiered machine control hierarchy is reliable.

The modular and hierarchical approach outlined here enables us to begin operations with deterministic software, and then effect a gradual transition into greater machine autonomy both as the technology evolves, and as experience is gained in operating many lunar base elements simultaneously. Eventual autonomous operation of a lunar base will introduce a new generation of performance goals capable of driving A & R technology to greater maturity than have undersea mining and the nuclear industry (two terrestrial applications which have already implemented the lower, deterministic levels of control quite successfully).

3.4 VERIFIED TERRESTRIAL ROBOTIC ANALOGS

The combination of capabilities proposed by our lunar operations scenario, and the integrated picture they paint of possible lunar operations, is different enough from past work to stimulate reasonable skepticism. A lunar base, while inarguably a space system and closely related to other space systems, is nonetheless a challenging and unprecedented undertaking. Although our study introduces, and relies on, novel approaches to difficult problems, precedents exist for virtually all its features. Much of the configurations,

hardware, and control technology required for lunar robotics is well established or will be derivative from near-term developments for undersea operations, the nuclear power industry, therapeutic and diagnostic medicine, and other space applications. Feasible solutions to the problems of planetary A & R, and sensible solutions to the problems of ground transportation, may however not be familiar to all aerospace professionals. For that audience, this study must bear the burden of proof that what we propose is indeed practical. In discussions with a variety of specialists, we have identified several areas of our work deserving particular justification: the straddler concept, unmanned work systems, robotic manipulation, and autonomous navigation.

TERRESTRIAL MOBILE CRANES - There are a number of terrestrial analogs to the straddler. They work in environments ranging from captive (on rails or tracks), to prepared ground, to the unpredictable pelagic conditions of the continental shelf. Railyards use captive gantries for reloading trailers among freight cars. Lumberyards use a similar machine to move and load piles of lumber. Yacht basins use a machine called a "comporter" to lift boats (especially sailboats) out of the water and place them in drydock, and then to refloat them. The US Army Corps of Engineers performs robotic mapping and sampling in and beyond the surf with the slow-moving Coastal Research Amphibious Buggy (CRAB). These analogs give us confidence in the mechanical advantages of mobile cranes for hoisting and positioning heavy and ungainly payloads, as well as transporting them carefully across uneven terrain.

UNMANNED WORK SYSTEMS - Unmanned work systems are the agents that will physically implement construction on the lunar surface. Most terrestrial examples are teleoperated, commonly enhanced by state displays, safeguards and tool controllers, and with increasing examples of off-line programming and operator-advisor systems. Terrestrial work systems are currently servicing oil rigs, working in nuclear power production and research facilities, repairing high-voltage transmission lines, performing seabed operations, and responding to hazards and cataclysmic accidents. In the last five years, such systems have recovered debris undersea from airplane and rocket failures, discovered and explored the *Titanic*, cleared debris from the Chernobyl disaster, and recovered the contaminated basement of the Three Mile Island nuclear power plant. Work systems routinely cut and repackage nuclear waste, and programmed cranes hoist and

handle construction materials at mid-rise construction sites. Crane operation from a hand-held button-box is standard operating procedure in work arenas from logging and foundries to truck deliveries and waste handling.

One example of a mobile, unmanned work system is the Workhorse, developed for service in nuclear accident response and shown in Figure 3-12. The Workhorse is a four-wheel-steer/four-wheel-drive electrohydraulic system. A telescoping boom deploys a manipulator and diverse tooling to 8 m height. Onboard electronics, computing and hydraulics are configured for fault-tolerance and functional redundancy, and are environmentally protected by a sealed, gas-filled enclosure.

Dual manipulators have recently been deployed from mobile bucket trucks, and controlled using close-proximity teleoperation --- a "man in the can" perched at the boom tip, or in the cab, in line-of-sight to the manipulators. The manipulators are hardened against high voltage and the deployment vehicles are insulated for servicing high-tension power lines in adverse conditions. Because this is a genuinely motivated (by hazard) and technically feasible application area that will be refined to end use on Earth, it is a near and informative analogy to lunar operations.

Subsea systems are the most diverse and accomplished family of unmanned Earth-based work devices. The analogies to lunar operations include: remote operations; sealing against the elements; and reduced apparent gravity from the effects of buoyancy. The physical forms of equipment range from seabed walkers, and crawlers for leveling rubble and servicing cables, to tethered free swimmers and remote ocean vehicles for servicing oil rigs, and autonomous navigators for military and search/rescue operations.

Technologies already existing or currently evolving from unmanned terrestrial work systems include: physical robot forms; actuator refinements; human interfaces and joystick controllers; synthetic displays; remote diagnostics; telemetry and command protocols; locomotor and manipulator controls; tooling; sensors; environmental conditioning; operations planning; and task management. These robots and their applications industries are pushing both the state-of-the-art and the experience base for unmanned work systems relevant for lunar surface operations.
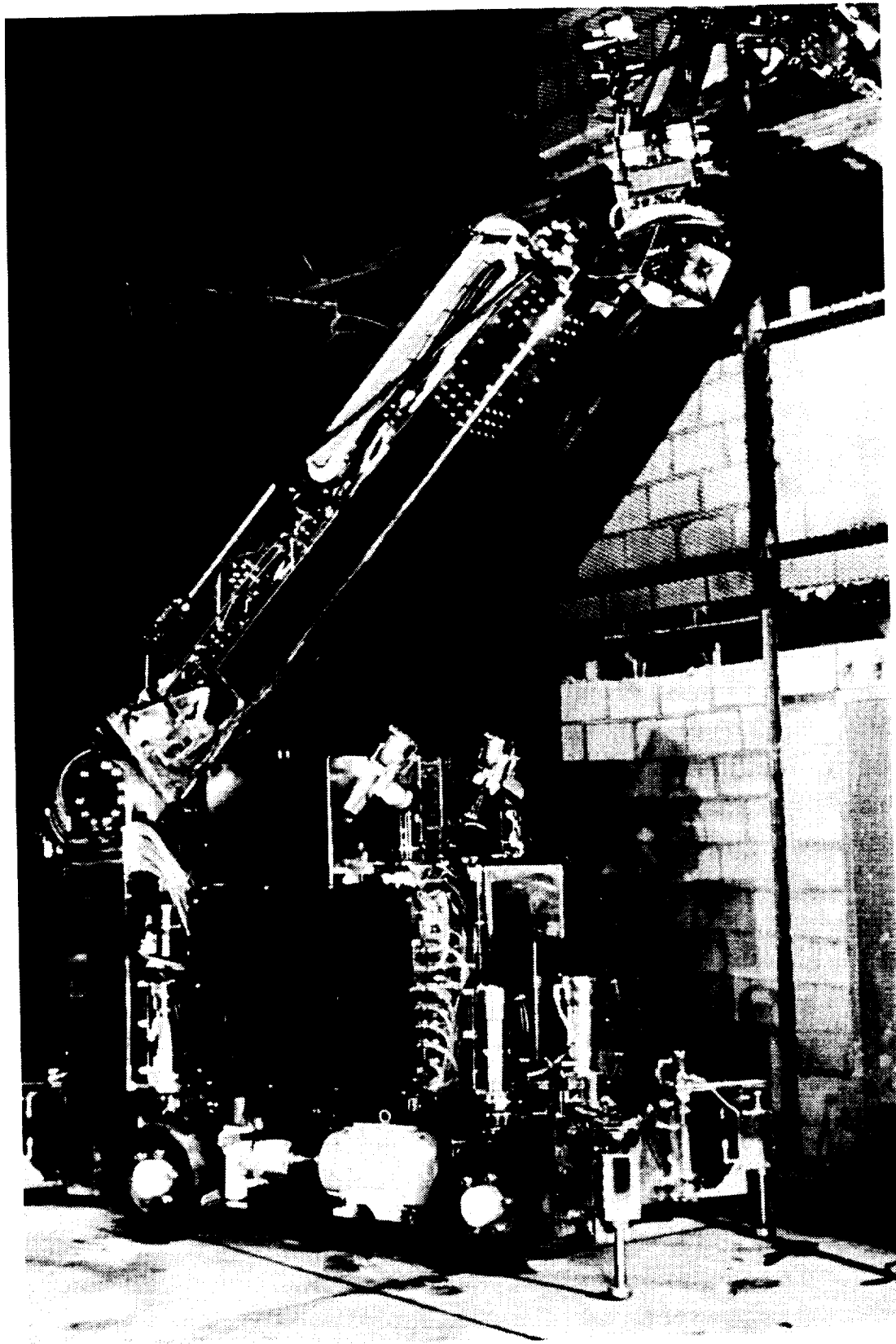
Figure 3-12   The Workhorse operates reliably in hard nuclear environments.

MANIPULATION - Manipulation is the physical means by which lunar surface facilities will be deployed, assembled and maintained. Manipulation is the most mature of the terrestrial robotic disciplines that will contribute to space operations robotics. The proven technology classifies into **programmed** (mostly factories and warehouses), **teleoperated** (hazardous and unstructured environments), **off-line programmed** (welding and task programming of work cells), and an emergent class: **vision-guided manipulation**, which is succeeding to overcome the limitations of executing programmed control.

Programmed manipulators are the backbone of factory applications, from car assembly and finishing to the production, inspection and packaging of electronics. They perform subtasks relevant to lunar facility construction such as assembly, bolting, and connecting.

Teleoperation is a classical control mode in which a manipulator is slaved to mimic the commands of a joystick or human gesture. (As defined by this study, driving a vehicle and controlling a crane are also categorical examples of teleoperation.) Some of the best terrestrial teleoperated manipulators have been developed for subsea and nuclear environments, situations that in fact motivated development of the earliest manipulation. Today's best high-dexterity manipulation is still developed and used by the nuclear industry, for such tasks as: installing retaining snap-rings; threading connectors; and handling fuel elements and other radioactive materials. Coarser, more forceful manipulators cut and package materials, deploy power tools and hand tools, and use simple grippers to set rigging hooks and handle heavier materials. Nuclear teleoperators also bear direct relevance to lunar base tasks associated with oxygen reactor maintenance. Several manipulator systems have been developed to perform remote inspection, cleaning and repair of reactor vessels analogous to our proposed oxygen plant in dimensions and access ways (Figure 3-13). A related, significant terrestrial initiative is also beginning for the same tasks in underground waste storage tanks. The versatility of teleoperation argues for its incorporation into any lunar work machine, if only for setup, troubleshooting and direct intervention by operators and onsite crew.

Off-line programming, a preferred mode of control relevant in the welding and manufacturing communities, generates manipulation trajectories from CAD models of the domain and templates of the task. This model-directed programming mode is the approach we advocate for many lunar base construction tasks.
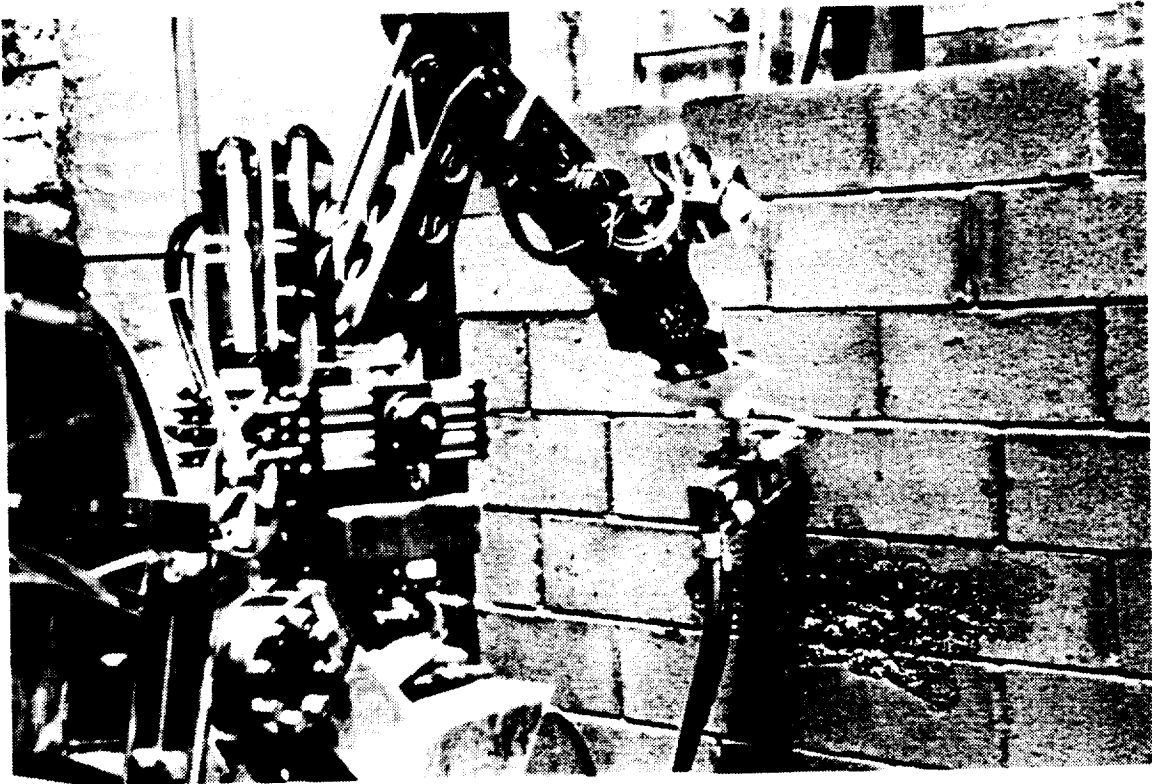
Figure 3-13 *Manipulation tasks akin to cleaning out a lunar oxygen reactor have been implemented terrestrially.*

Vision-guided manipulation, in which activity is guided from task models and domain models with ties to the physical world through sensors, is a very promising development area. This is a significant thrust of the manipulation research community, and is now moving from laboratories to practice with immense impact on robot task competence.

AUTONOMOUS NAVIGATION - Lunar construction activities differ from fixed manipulation in that the base site exceeds the range of any manipulator, and calls for mobility. Locomotion for surface construction differs from that required for orbital

facilities (free-fliers and prehensile walkers), in that surface equipment is gravity-stabilized; leading to a mix of physical advantages with few liabilities. Finally, navigation for lunar base operations differs from that required for planetary exploration. At a base, it is possible (and prudent) to exploit detailed pre-knowledge of the terrain, as well as the invaluable advantage of site-fixed positioning, and the significant a priori information available in a planned, constructed environment.

Unmanned ground vehicle locomotion and navigation are major terrestrial initiatives that have produced demonstrated analogs relevant to lunar surface operations. Lunar sites will be readily traversable by wheeled or tracked locomotors, which are well-understood through terrestrial analog. Prudent site selection on the Moon (in this case determined partly by resource availability) can preclude the very rugged terrain that might otherwise motivate legged machines, prehensile grapplers, or other exotic forms of locomotion for other space applications.

Figure 3-14   The NavLab is a testbed vehicle capable of autonomous off-road navigation.

Demonstrated terrestrial mobile robots with relevance to construction and mining on the Moon include the NavLab, which has driven miles of long-range, high-accuracy off-road navigation at high and low speeds (Figure 3-14). Although the NavLab has demonstrated neural net and blackboard controllers based on machine interpretation of surroundings, a noteworthy mode of off-road navigation utilizes offboard position estimates to great advantage. The NavLab commonly uses scanning laser ranger vision and camera vision to model and verify its intended path, and to safeguard itself and surroundings against collision. The technologies are directly extensible to the guidance of equipment for mining, excavation, haulage, material transport, component handling, and personnel transport at a lunar site.

The Terregator has demonstrated significant performance in more tactical, close-order navigation, the type relevant for driving and positioning construction machines. The Terregator is a desk-sized, all-terrain robot vehicle that has navigated autonomously using sonar, scanning laser, single and stereo cameras (Figure 3-15). Of particular note are navigation successes in underground mining environments. A current initiative utilizes the Terregator in developing capabilities for the automated mapping of hazardous waste sites by mobile robots, a close analogy to lunar site navigation.
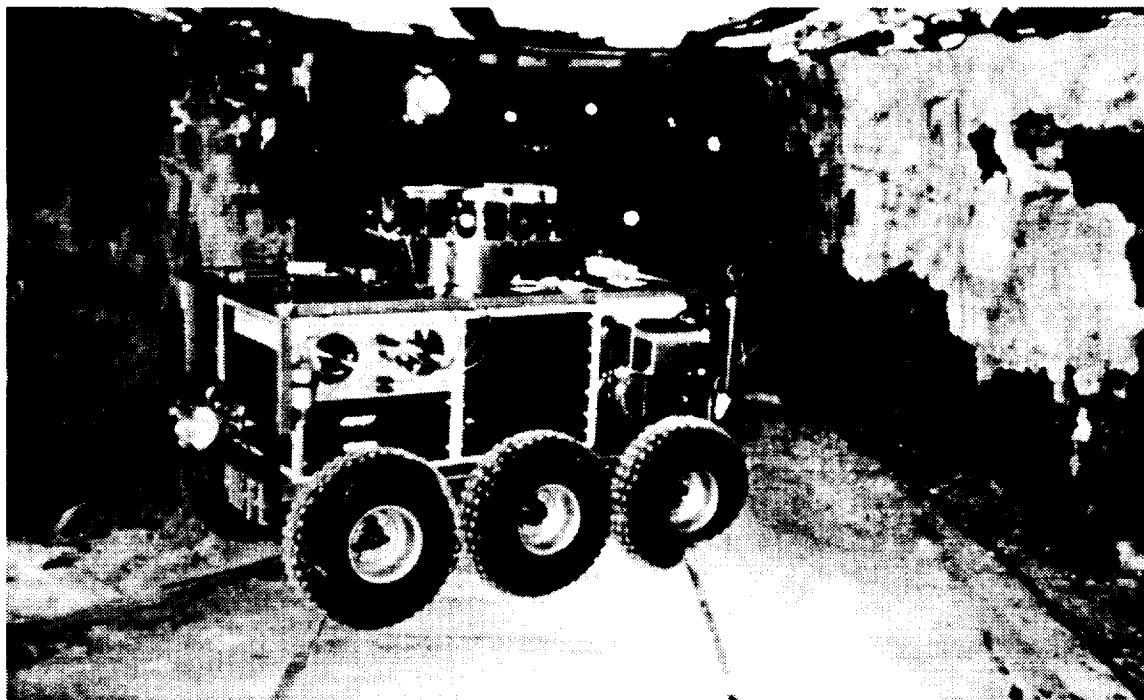
Figure 3-15 The Terregator uses multi-sensor data for close-order tactical navigation.

DoD and DoE application programs (such as the Automated Ground Vehicle Testbed, Autonomous Land Vehicle, Tactical Multi-purpose Autonomous Platform, and Robotic Command Center) have driven outdoor vehicles on- and off-road by teleoperation, autonomy, and mixed modes. All of these have pursued man-in-the-loop control with varying degrees of onboard functionality. These programs are developing off-road navigation using teleoperation and positioning beacons for surveillance, weapons targeting and site monitoring.

NASA's vehicle programs are also noteworthy. The Jet Propulsion Laboratory is now demonstrating unmanned traverse of outdoor terrain, driven by the Computer-Aided Remote Driving (CARD) system. The manned Apollo LRV, and the robotic *Lunakhod* which crept on the Moon twenty years ago, both provide invaluable first-hand insight into lunar navigation. A number of research initiatives have broken the important abstractions for unmanned navigation, and are evolving performance in field demonstrations. Carnegie Mellon University and other institutions are developing unmanned walkers; derivatives of their perception, planning and physical controls are directly applicable to mobile lunar equipment and operations.

3.5   CONTINGENCY SCENARIOS

Even an early lunar base will be among the most complex space systems ever built, with diverse subsystems and inherent problems. Additionally, there is a lot of robotic capability in our plan which has not yet been demonstrated in space, as well as capabilities in autonomy not yet demonstrated at this scale of operations. As noted earlier, envisioned problems are rarely the ones that actually cause trouble in advanced space systems. Rather, it is mostly the problems not imagined beforehand that end up being the toughest ones. Effective contingency planning includes four activities:

1)   Thinking through as many problem scenarios as possible, in all phases of development, and prioritizing them according to likelihood and severity.

2)   Responding to them in the design process as much as is reasonable, by incorporating resiliency into the hardware and software.

3)   Responding to them in training, by preparing robotic operations crews and in situ crews for a wide-ranging and versatile array of activities.

4)   Supporting a flexible operational response once operations begin, by providing timely access to information and analysis, by reprogramming, by safing equipment to stabilize an off-nominal situation, by developing a versatile array of tools, and (where necessary) by scheduling onsite intervention.

Of these, item (4) is a programmatic issue beyond the scope of this study, except to say that the long-term operation of any system must play a central role in its initial design. Item (3) is addressed in section 3.6. We have made a concerted effort to accommodate item (2) in the equipment and operations designs developed by this study. What follows addresses item (1), and consists of a list of most likely "representative failures", which we used for design guidance.

1)   **Failure to rendezvous or dock:**
        • Due to automated systems failures or bad rendezvous computations
The fix is repeated attempts, if proximity is periodic or can be recovered by further orbit corrections, followed ultimately by sending a replacement lander or orbiter. Transportation system failure modes are beyond the present study scope, except insofar as they affect the delivery schedule.

2)   **Landing problems:**
        • Hard landing, landing site miss, or tilted lander inaccessible to automation
The straddler could offload a lander in practically any mare terrain. To be inaccessible, even in some salvage fashion, to the straddlers, an off-nominal landing would have to be rather severe. Depending on severity, the most likely fix would be to send a replacement flight. The pad might have to be cleared, reconstructed, or even abandoned, with salvage only for raw materials. The likelihood of a hard landing may be greater later in an operations mode, with increasing traffic and less conservatism. The base response capability would be greater then, too.

3)   **Mechanical problems:**

- Failure to fit, hook-up, deploy, or operate; blockages, hang-ups, etc.
- Line connection leaks or shorts (EPS, O_2, H_2, H_2O, NH_3, etc.)
- Rock jams in miner

These difficulties will be exacerbated and compounded by extreme thermal cycles, and dust, dirt, and grit in the "no-wash" lunar environment. The details of connections, riveting, and other delicate robotic operations may be more difficult than the major operations of controlling vehicles, digging trenches, grading surfaces, etc. The probable fix is a teleoperated attempt using other equipment around the base, followed ultimately by a crew visit for EVA.

4)   **Vehicle stoppages:**

- Due to tip-over, hang-up on rocks, traps, getting stuck in soft regolith, etc.

Performance of all vehicles is a concern in uneven terrain, rock fields, and crater fields. This poses the greatest problem before roads are built, around active construction sites, and during scientific forays outside the base. It is as yet unknown whether autonomous or manned driving will result in more stoppages. The fix is correction by onboard tools (manipulators), followed by rescue by another vehicle, then EVA crew intervention, and finally vehicle replacement.

5)   **Software and computer glitches:**

- Failure to operate, command rejection, latch-up, single-event-upset, etc.

Radiation is a major cause. The primary fix is prophylactic, performed in preflight software design by using error detection and correction methods: check bytes, alternate paths, backup systems, rewrite flexibility, and parallel computation by different codes. Post facto fixes are timeout reset interrupts, and manual takeover of safety-critical device control. Processor upgrades (changeouts) are the ultimate fix.

6)   **"First of a kind" design problems:**

- Unexpected interaction between systems in "cross-system" failures.
- Actual operating zones sometimes outside of design operating limits.
- Failure modes are usually not as planned or predicted in preflight analyses.

These problems are by definition unexpected due to our lack of complete visibility into the unknown. They are inherent in every space system ever built (note for example the number of STS design changes post-*Challenger*). The fixes are designed-in or added redundancy, and repair.

7) **Problems due to regolith unknowns:**
   - Tool breakage on submerged inclusions (as when a farmer breaks a plow point)

The primary fix is prophylactic, relying on the subsurface site survey to avoid such trouble spots. The ultimate fix is tool replacement.

8) **Solar cell degradation:**
   - Due to dust, meteorites, base-generated contamination, etc.

The fixes are emission controls, automatic cleaning, and eventually replacement.

9) **Damage due to meteorite strikes:**

The probabilistic frequency, energy distribution and damage modes all need to be understood, and can benefit from in situ study. The fix is first protection, then repair or replacement.

10) **Communications and video failures:**
   - Reasons are multiple and historic

The fixes are alternate paths, repair and finally replacement.

This list can only outline problem categories; ongoing efforts to plan exploration missions will provide more detailed opportunities to evolve more complete contingency scenarios. Working these problems along with concept designs is crucial to advance credibility along that path, and help prepare for the unexpected.

3.6 CREW SUPPORT ROLE

Because the purpose of this study was to discover and define the maximum potential use of A & R for lunar surface operations, we consider here the role of human crews in support of that activity. Of the 15 flights planned during our base buildup scheme, only two are crew-carrying, and stay only for one lunar cycle each. This ratio, and the "supporting role" terminology, should not in any way be taken to propose or

endorse the notion that human crews are somehow secondary for the complete and productive functioning of a lunar base. On the contrary, the purpose of introducing A & R techniques into lunar base buildup and operations is to offload many necessary, but nonetheless menial, hazardous or repetitive tasks from the human crews. Lunar crew time is so valuable that it should be reserved when possible for truly productive, interesting activities that require uniquely human qualities and directly advance our understanding of, and capabilities in, the space environment.

NORMAL CREW ACTIVITIES - In analyzing the best uses of human time in our scenario, we distinguish among **investigative** or science work, **developmental** work such as improving devices and processes in situ, and **service** or repair work. By "science" we mean both pure and applied science. That is, two fundamental purposes of human presence on the Moon are to learn about the Moon and space from that vantage point, and to learn how to live in deep space by empirical engineering. Optimally, most of the crew's time would be spent in these pursuits, since they address directly the top-level programmatic goals of a lunar base and strictly require human capacities for judgment, initiative and intuition. Routine sampling can be done robotically, and the machines we propose can be used in a variety of ways for telepresent science. It is likely that most planning, analysis and characterization will be done IVA. In this study, we do not address specific investigative crew activities, simply accepting that our primary goal is to maximize the opportunity for such work.

Developmental work consists of crews observing, learning from and adjusting the performance of tools, machines and systems to enhance productivity. These activities may prove to be the most productive of human activities on the lunar surface, exploiting as they do human capacities for workarounds, inspiration and innovation. The international history of manned space programs proves certainly that this "tinkering" type of activity is extremely beneficial, and sometimes critical. Planning for equipment modifications can begin here, and designs for new ORUs (space replaceable units) can then be developed for installation during later manned visits. A versatile array of tools is essential to facilitate developmental work, and a modest supply of raw stock (sheet, tube, wire, fasteners, and so forth) would be a valuable investment. We can also expect that budgeted equipment spares will be adapted for unplanned field modifications as needed.

In our scenario, service work is done by crews and machines together, each contributing optimally according to the task. The robots are employed primarily for R & R: performing routine and telepresent inspections; removing parts identified as faulty and installing spare units; transporting faulty and repaired units around the base; and placing faulty units into and removing repaired units from the evacuated workshop module (Figure 3-16). Inside the workshop module (once pressurized), detailed repair work requiring human capacities for dexterity, troubleshooting and finesse can be accommodated productively. The primary EVA servicing and maintenance tasks for crew should thus be limited as much as possible to inspection, and verification of nominal performance or the need for servicing. After all, tasks that must be accomplished by suited EVA crewmembers will be time-consuming, mainly because of transportation around the base and because of safety considerations, such as sharp corners and edges, and hazardous materials, temperatures, pressures and stored energy devices. Also, it is reasonable to assume that EVA must continue to be a two-person activity, so it is by definition labor intensive, and is certainly operationally costly.
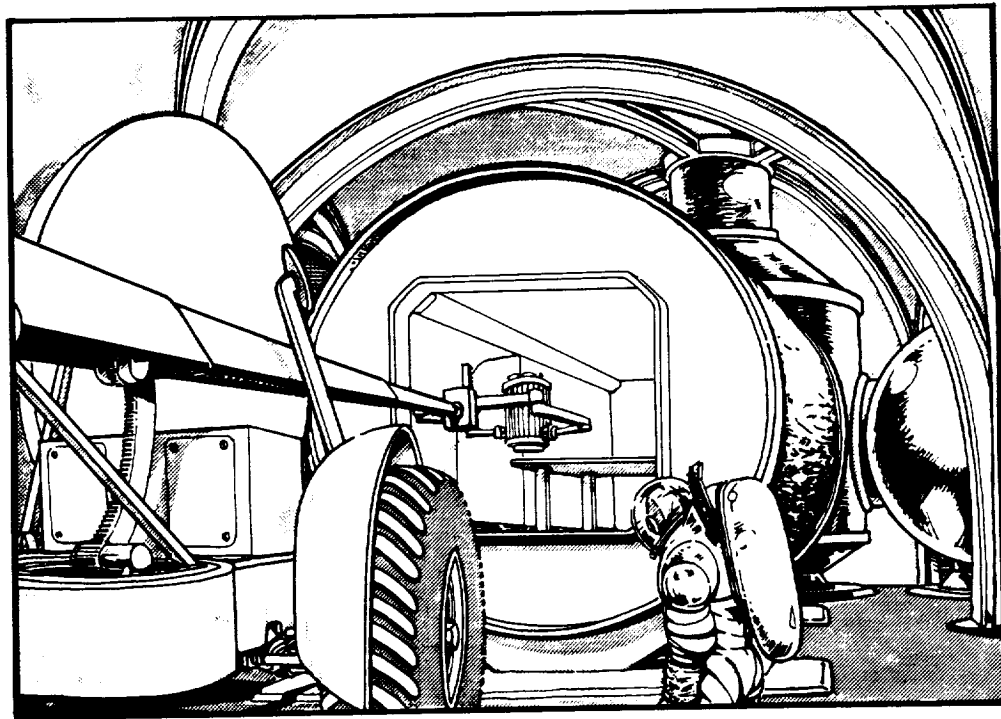
Figure 3-16   A truck places a defective straddler steering unit inside the workshop module for disassembly and repair by crew.

The staged maintenance concept is based also on factors other than the costs just outlined. Past work on spares logistics for crew-carrying deep space missions indicates that a reasonable probability of mission success can only be attained with unit replacement at the component (circuit card, valve) level. This in turn implies repair capability at or below that level, as well as sufficient replacement parts. And a sufficient supply of parts can only be modest (and therefore practical) if there is a high degree of commonality among them. Optimally, a large space system like a lunar base should contain a large number of interchangeable parts. Detailed prospects for meeting this objective, particularly for a small startup base, remain unstudied. Performing repair work at such a detailed level requires not just ORU subsystems, but openable ORUs. Particularly in an environment containing dust with a high metallic fraction, opening an ORU requires special care. Clean EVA gloveboxes seem a compromise solution, since suit gloves are already severely limiting --- another glove layer cannot help dexterity. However, with a reserve of dormant ORUs, robotic R & R can defer component-level repair work without interrupting base operations. Critical failures would be safed automatically, and trigger alarms to alert the crew for immediate attention. But non-critical failures would be managed by the base controller: worked around, scheduled for R & R if necessary, and programmed for crew attention during planned maintenance periods. A batch of faulty units would be collected and brought inside the workshop module at one time, to minimize air makeup losses. Working comfortably and freely inside, the crew can clean, open, repair, test and reseal the ORUs, readying them for further active life as needed.

In the base buildup phase, when crews are not continually available for repair work, maintenance activity will not yet have settled into a smooth routine. Thus it is unclear whether base productivity will be enhanced or suppressed during early crew visits, although we would expect enhanced robotic productivity once the crews had completed adjustments and departed. The primary reason for bringing crew periodically before the base is completed is so that they can check up on its progress at critical points: just after the habitat is completed, shielded and started up; and just after the first oxygen reactor has finished its first batch. Routine servicing and maintenance should continue during visits, while the crew accomplishes their high-priority overall inspection and evaluation. Their next priority will be qualifying processes with pilot equipment brought as payload, and monitoring the experimental expansion of the robotic operating envelope. Their final priority will be completing the backlog of deferred maintenance jobs to restore the spares stockpile. The crew presence allows changing out and repairing components which have

been operating degraded, and the concentration of such efforts may well reduce base productivity during that time. Running the most complex base processes only during lunar days leaves the lunar nights available for IVA data analysis, repair work, and planning. We anticipate that these uniquely human tasks will fill the visiting crews' dark fortnights. More regular human presence later on will increase the amount of data and planning requiring attention, and improve equipment failure response time. A base operated with A & R, but sustained, monitored and improved by human crews, shows the greatest promise for efficiency.

CREW TRAINING - It will be essential for crews to contain people extensively trained for roles as systems managers, chemists, process engineers, roboticists, field engineers, field scientists, electronics technicians, mechanics --- all the skills necessary to make appropriate adjustments to the base and extract the greatest productivity from it. The plethora of specialties required probably precludes encapsulating the necessary expertise in each crew member, but the limitation of small crew size means that extensive cross-training will be vital. The high-capacity data links between Earth and Moon required for supervising robotic operations will facilitate close coupling between Earth-based experts and surface crews. For refresher training and guidance during maintenance activities, the crews will have available an information management system analogous to that on SSF. It will store design schematics and performance parameters, guide crews through procedures, and record their actions and results.

The crew should be involved early on in the design and development of equipment and processes for robotic assembly and operations (as they were represented by crew consultants even on our study team). Such involvement assures inclusion of the human operational viewpoint (essential to make all systems controllable by people as well as machines), and provides invaluable crew training. Once the robotic surface operations begin, it would be prudent to include the crew in the teleoperator corps on Earth. Their direct participation should increase as much as possible up until their assigned missions. They should also be intimately involved in the more nominal supervisory activities; in-depth familiarity will prepare them most effectively for whatever they might encounter on the Moon during their visits. Finally, upon return the crews should participate directly in equipment modifications to prepare for later flights.

Contingency preparation requires particular attention. Experience has shown that those failures for which one is prepared seldom occur. Hence the crew should be at the peak of their training as the surface operations begin, so that when the unexpected occurs, training can be concentrated on the contingency. The crew must be involved in developing new procedures and in determining the need for special parts and tools.

Two general contingency scenarios requiring crews can be considered. First, for failures that can be dealt with by robotic workarounds, crews will of course participate in developing and executing the fix from Earth. But experience also implies a substantial probability of a second kind of failure: one requiring in situ human intervention before the next scheduled manned mission. When waiting is not practical, either because of the program schedule or because the failure increases the risk of further failures, a dedicated mission needs to be mounted. It took only 10 d to prepare tools, equipment and crew training for the repair mission to the damaged Skylab workshop. In the lunar case, however, it would be appropriate to allow something like six to ten weeks on Earth to ready a contingency mission. Another two weeks would be reasonable at SSF to load and check out the transfer vehicle, and allow the crew to adapt to microgravity. A further week would be required for translunar flight, transfer to the lander, and descent. This 9 to 13 wk response time total assumes an ETO vehicle available on the pad, and optimal SSF-LLO transfer alignment. Figure 3-17 outlines the worst-case response time for an unscheduled crew trip to the lunar surface. For intercessional fixes not requiring Earth-launched equipment, having trained operations crews already available at SSF would dramatically reduce the response time. In the best case, only vehicle preparation and flight would be required. The repair crew could study the problem, and plan strategy, in transit. This approach would of course prohibit taking advantage of the unscheduled visit to do much more than perform the needed repair. The appropriate response would obviously vary with failure severity, and remains untraded.

The complexity, cost and delay of sending human crews to effect emergency repairs in any case provides a strong motivation to design robust A & R capabilities into the base. Clearly, the hierarchy of preferred responses to non-catastrophic failures is to: first, limit their occurrence by proper design of equipment, procedures and margins (be smart up front); second, limit their impact by designing multi-path procedures not subject to simple interruption (have more than one way to skin a cat); third, fix, compensate or at least stabilize them by innovative Earth-based supervision and control of the in situ equipment

- Determine precise failure or narrow possibilities to a few   2 wks

- Devise fix   4 wks

- Acquire and qualify replacement parts (probably available)   *   ---

- Acquire flight-type training hardware   *   ---

- Train crew   *   ---

- Prepare crew transfer vehicle (assume SSF crew performs)   *   8 wks

- Launch crew   ---

- Crew checkout of transfer vehicle   2 wks

- Delay for best Earth-Moon alignment   4 wks

- Translunar flight to landing   1 wk

* assumed to be parallel operations	TOTAL	21 wks

Figure 3-17   *The worst-case preparation time for Earth-based repair crews to respond to a lunar surface failure depends strongly on their transportation system readiness.*

(robotic workarounds); fourth, send a dedicated mission with people and/or replacement equipment. This same hierarchy is as appropriate for managing in situ EVA responses to operational failures, as it is for managing response missions launched from SSF or Earth during the buildup phase. In lunar surface operations as in other space activities, human crews will continue to be the final answer to problems encountered in expanding human presence.

3.7 ENVIRONMENTAL COUNTERMEASURES

The lunar environment presents a challenging array of complications for machinery and electronics. Figure 3-18 outlines the major considerations which must be accommodated by equipment transported through space to other planetary surfaces.

Careful attention to tribology is enabling for lunar mechanisms. Equipment on the Moon is prey to all the familiar and well-studied space lubrication problems of vacuum (metals cold-weld, greases turn to glue, liquids evaporate and intercalation fails) and temperature extremes (ranging from -170° C at night to +110° C during the day). But the Moon also introduces potentially severe abrasive wear. 50 % of the regolith is finer than the human eye can resolve (about 70 μm), and this highly abrasive dust sticks electrostatically to virtually everything it touches. The Apollo experience is well-known. Macroscopically, the agglutinate-rich regolith clumped and built up in many places; for instance, it obscured the stair treads of the LM ladder. Microscopically, the dust adhered to all kinds of equipment. Crew suits became grey from the waist down, after just a few

	Space	Planetary Surface	Effects
Pressure	Hard vacuum (10 E-6 to 10 E-15 torr)	Low pressure to hard vacuum (1 to 10 E-12 torr)	Polymer outgassing, liquid lubricant failure, galling & binding
Temperature	- 100 C to 100 C	- 170 C to 110 C	Dimensional changes, material degradation, embrittlement and softening
Gravity	μ g to 1 g (artificial gravity)	m g (Phobos) 0.17 g (Moon) 0.38 g (Mars)	Weight & potential energy as terrestrially
Lighting	High contrast (pitch darkness to blinding sunlight)	High contrast (lunar diurnal cycle lasts 28 days)	Visibility & depth perception difficult, sensor saturation
Contaminants	Atomic oxygen in LEO/ Vehicle outgassing Hypervelocity particles	Adhesive, abrasive lunar regolith Windblown martian fines, possibly corrosive/toxic	Material degradation, Tribological problems, Countermeasures required

Figure 3-18 Space and planetary surfaces introduce unique combinations of environmental challenges.

hours of walking, riding and falling. Camera lenses were routinely cleaned at each rover stop (repeatedly wiping the thin dust film off, as the Apollo crews did, would quickly ruin the lens coatings of more permanent equipment). And the dessicated fines inevitably brought inside the LM cabin occasionally caused temporary breathing discomfort for the crew upon repressurization (incidentally, lunar dust in air has the odor of burnt gunpowder).

For robotic systems operating around lunar dust, we propose overlapping countermeasures, both prophylactic and compensatory. First, we try to keep dust off. There is no atmosphere to suspend lofted particules, and the creeping motions of most robotic activity will not "kick up" much dust. Human activity and lander exhaust plumes are thus the dominant sources. We have designed platforms and bases to keep critical components at least 1 m up off the ground to minimize the former, and debris barriers for intercepting ballistic blast ejecta at the landing pad to virtually eliminate the latter. We have paved the ground around critical elements (PV arrays and the LLOX depot, for example) with a compacted mixture of gravel and sand to limit dust production by wheel churning.

Second, where appropriate we try to keep dust out. Some components, like electronics, many sensors, and traction-drive motors, can be hermetically sealed against dust. Subcomponent maintenance on these (and other, incompletely sealed units) would be accomplished by robotically replacing the entire ORU, then removing the faulty unit to the pressurized workshop, where human crews can clean, open, repair and reseal it. In addition, the outer surfaces of sensor lenses, solar arrays and radiators must periodically be cleaned in situ. Since the dust film adheres electrostatically, a robotically-positioned electrostatic precipitator should be able to remove most of it; we have listed such a device as part of the robotic toolset. Another approach which shows promise for protecting sensors and larger windows is multi-layer, optical polymeric films applied during manufacture. When the outer surface degrades excessively, it can be peeled off to reveal a fresh surface layer. Geometrically commplex equipment may require compressed gas blasts to blow dust away periodically. Alternative methods will probably be used simultaneously, rather than exclusively.

Incidentally, total unit closure is independent of the need for thermal control in vacuum, since convective transfer is not an option. Conduction to other hardware and ultimately radiation to space are the only means available for rejecting waste heat. The adequate thermal conditioning of equipment units, particularly electronics, for long-term

lunar use is an area requiring engineering development. To simplify thermal management (by avoiding active cooling), such subsystems must be able to run somewhat hot. Cycling between daytime and nighttime equilibrium temperatures may exact the greatest toll on systems.

Finally, where necessary, we "overwhelm" the dust's effects. Many gears and joints just cannot be kept dust-free, because they are either part of dust-handling systems (miner), located under dust-shedding mechanisms (as is the truck chassis), or even operate directly in the regolith (wheels, excavation tools). Our approach here is to acknowledge and address the inescapable. Configuring mechanisms openly will let all but the inevitable dust film fall through, preventing macroscopic binding. Then, sizing critical bearing surfaces robustly, and treating them specifically for surface hardness, will mitigate abrasive wear. Oversize components and high power are the typical terrestrial solution for heavy construction equipment which must operate in difficult environments, but both are extremely costly in space. We expect the "clever materials" approach to be favored generally over the "brute force" approach for early lunar systems. Promising alternatives -- again, not mutually exclusive in an integrated design -- include plasma deposition of diamond-like carbon (DLC) and real diamond films on hard alloys. In any case, appropriate joint and bearing designs will feature these specially treated alloys as replaceable inserts in the mechanism. When nominal tolerances or smooth functioning become impaired as the active surfaces wear out, such mechanisms would be disassembled in the field, and their inserts replaced robotically.

Molybdenum disulfide is still the best dry vacuum lubricant available. Relatively long-lived, low-friction surfaces can be made using tough applied coatings (including outgass-resistant polymers like polyfluorotetraethylene (PFTE)) impregnated with chalcogenide materials such as MoS_2. The essential problem with dry lubricants is that relubrication means replacing the part. Again, critical surfaces treated this way should be replaceable inserts, and as interchangeably common as possible, to facilitate robotic R & R and minimize transported equipment mass. Summarily then, we expect mechanisms optimized for lunar surface use to be "knobby", open, standardized parts with replaceable, specially-treated active-surface inserts.

For terrestrial applications, hydraulic mechanisms have distinct weight and power advantages over all-electric power trains. However, hydraulic systems appear undesirable in the lunar environment due to weight, leakage and their strict requirements for tight,

moving seals. The usefulness of hydraulic systems in dirty terrestrial environments is so great, however, that rejecting them out-of-hand for planetary uses would seem premature. By the time of an advanced base, hydraulic technology may be able to trade favorably for specific, high-power uses. Since that technology is not yet in place, and since we were able to design the reference scenario without calling for it, we have avoided hydraulic systems entirely. We specify rack-and-pinion (R & P) drives for robotic mechanisms requiring a large range of motion. This includes extension arms, swing arms, actuated pivots, and outriggers. The R & P approach follows our design philosophy outlined above, allowing relatively open, contamination-tolerant joints with replaceable, hardened bearing-surface inserts.

3.8 RELIABILITY ANALYSIS

For long-term lunar operations, the challenging and unprecedented native conditions make system reliability a vital, new area of investigation. Prior to this study, no quantitative analysis of the overall reliability of lunar base systems had been done. Data from the Apollo program are available but limited (they do include relevant test results for the LRV). The goals of a complete reliability analysis would be to:

1) Identify the mission-critical system elements by means of high-level failure-mode, failure-effects, and criticality analyses.

2) Establish credible failure rates for these elements, utilizing existing historical data bases.

3) Evaluate the feasibility of A & R repair capabilities augmented by human intervention.

4) Define on-site spares inventories to support the reference test/checkout/repair concept.

Items (1), (3) and (4) are handled by other sections of this report, as follows. For an initial base, the presumption of minimal emplaced mass makes it difficult to find elements whose uncompensated failure would not compromise mission success. "Mission success" (the nominal completion of primary mission goals) for a lunar base featuring a blend of robotic and human activities, is quite distinct from success based on "vital" criteria (by strict definition, those invoking life-threatening circumstances). After all, most of the equipment (as measured by total mass) in our lunar base reference concept has virtually nothing to do with the ability of the base to sustain human crews. Instead, failures are much more likely to interrupt oxygen propellant production. The most failure-prone activities that do affect the crew support systems occur before crew are even sent to the Moon. We have addressed the topic of degraded equipment performance and contingency scenarios in section 3.5. We have already discussed the feasibility and appropriateness of a complementary robotic/human maintenance scheme in section 3.6, and designed the resulting R & R requirements into our base elements and integrated scenario. The topic of spares inventories is covered in section 3.9.

The detailed definition of base elements already required by our functional analysis allowed us also to estimate system reliability quantitatively. This section details item (2) above, the development of credible failure rates for the equipment designed into the reference scenario. We undertook to perform a first-generation analysis of component failure in the lunar environment, and of the systemic result of those integrated failures. Our results are, of course, coupled closely to specific design and analysis assumptions, and represent just the first effort in this field. Nonetheless, useful conclusions emerged, and we anticipate that this work can serve as a point of departure for future work on the reliability of lunar equipment. In particular, we validated the usefulness of a methodology for generating quantitative results, and anticipate refining it in the future.

The ground rules for our reliability assessment were that:

1) Failure rates were to be based on current available data (published from 1960 to 1985), adjusted according to projections of the effects of the lunar environment.

2) Equipment design would be optimized for lunar conditions according to contemporary understanding, although the equipment used for failure rate source data was optimized for various Earth and near-Earth environments.

3)   Random failure characteristics for both mechanical and electrical equipment are the same, accurately represented by the classical reliability "bathtub" curve.

4)   Software reliability was not addressed; while critical, it does not depend on specifics of the lunar environment.

5)   Major lunar base operations would occur during daylight. Critical components were assumed to be kept warm by stored power during lunar nights, although detrimental effects of thermal cycling were considered.

6)   Reliability of the habitat system was not addressed. The majority of its systems prone to failure are inside the pressurized system, and internal subsystems were defined outside the scope of this study.

7)   A failure was defined as the off-nominal performance of a component or system, regardless of severity.

The methodology used was to:

1)   **Develop the system "end item", or element, configurations; then identify their major subsystems and components.** Table 3-3 lists comprehensive subsystem inventories for the mobile, and major fixed, base elements: straddler, truck, rover, miner, habitat system, oxygen reactor, LLOX depot and RFC module. These lists were used to develop first-order part and mechanism counts for those elements. (The habitat system breakdown is included for completeness, although it was not included in the reliability analysis. The PV unit breakdown listed along with the habitat system was used.)

2)   **Collect generic failure rate data from available sources,** including reports on the LRV, on-orbit spacecraft, and military, flight and electronic systems. Obtaining usable source data proved quite difficult, as very few concise accounts of relevant component reliability exist, and those that do are limited in scope. A more complete analysis would also include data from other relevant environments, such as mining equipment, cement manufacturing plants, and automotive and construction vehicles. Comparable subsystems for which reliability data were available were then matched up to

STRADDLER (2 in reference)

Major subsystems for each vehicle:

Upper structural frame, with 3 corner leg idler/pinion guides/drives
Lower structural frame, with 3 corner leg idler/pinion guides/drives
9 hoists mounted on upper frame
Chassis-mounted hoist-cable pulleys
3 independently operated leg columns
3 leg-mounted rack inserts
3 independent drive/steering/hub modules
3 3 m all-metal wheels
3 brake/wheel-lock sets
2 RMS systems on lower frame
3 extension jacks on lower frame
12 tracking solar array units with power processors
Peaking batteries
Communication transceivers
Navigation sensors, including: laser ranger, video & beacon antennas
Local lights
Onboard status sensors, including: temperature, strain, level & acceleration
Task sensors, including video
Coordinating and task planning processor/memory
Power cables
Data and control signal cables
Cable harnesses/guides/pullers for legs, hoists, RMSs
Power and structural connections for miner
Power connector (for external charging use)

Control systems:
PV arrays
Frame drives
Wheel modules
Brakes
Jacks
Hoists
RMSs
Communications
Navigation

Motor count:
3 drive
3 steering
6 leg drive
9 hoist
12 PV array elevation
12 PV array azimuth
RMS joints (taken as integrated system)
Transceiver/navigation sensor drives (taken as integrated systems)

TRUCK (2 in reference)

Major subsystems for each vehicle:
Chassis
2 axles
4 hub drives
4 wheel mounts
4 2 m all-metal wheels
4 brake/lock sets
Steering mechanisms
Suspensions
Telescoping high-reach extension boom
Boom end-effector socket
Extension mechanism, including: R & P, cables, pulleys, idlers
Boom nimble
4-DOF strong wrist
4 outriggers
Rechargeable batteries
Communication transceivers
Navigation sensors, including: laser ranger, video & beacon antennas
Task sensors, including video
Onboard status sensors, including: temperature, strain, level & acceleration
Coordinating and task planning processor/memory
Crew command station
Local lights
Recharging cable and connector
Power cabling
Data and control signal cables
Tow hook
Convertible dozer/bucket
Dumping storage bin
Attachments (listed in section 2.5)   /

Control systems:
Vehicle drive, steering & brakes
Boom orientation and extension
Boom end attachments
Front wrist & dozer conversion
Trailed attachments
Outriggers
Dumping bin
Communications
Navigation

Motor count:
4 vehicle drive
2 steering
Boom azimuth
Boom elevation
Boom extension
4 outrigger deploy
4 front-wrist
Dozer - bucket conversion
Bin-dump
Transceiver/navigation sensor drives (taken as integrated systems)
Trailed attachments (compactor vibrator, bucket-wheel drive and lift)
Boom attachments (dual RMSs and sensors taken as integrated systems)

ROVER (2 in reference)

Major subsystems for each vehicle:
Chassis
2 axles
Steering mechanism
Suspension
4 hub drives
4 wheel mounts
4 1 m all-metal wheels
4 brake/lock sets
Crew tool crib
Hauling bin
Site survey sensors (removable)
Navigation sensors (robotic and manned)
Onboard status sensors
Communication transceivers
Local lights
Coordinating processor/memory
Tracking PV array
Peaking batteries
Sensor boom
2 removable seats
Light dozer blade & attachment mechanism
RMS, mount & end effectors

Control systems:
Vehicle drive, steering & brakes
Sensor boom
RMS
Communications
Navigation
Site survey

Motor count:
4 drive
2 steering
PV azimuth
PV elevation
RMS (taken as integrated system)
Sensor boom (taken as integrated system)
Transceiver/navigation sensor drives (taken as integrated systems)
Site survey equipment activation drives (taken as integrated systems)

MINER

Major subsystems:
7 connection mechanisms for attachment to straddler
Chassis
Miner mouth activation mechanisms
Ripper
Grader
Scalper (cowcatcher)
Scraper tool
Lifting crowd-hopper
Hopper lift
Top dust guard
Hopper dump mechanism
Hold-up bin & release mechanism
Passive grizzly scalper
Rock chute (with internal baffling to break fall)
Rock bin & dump mechanism
12 sieves (2 stages of 6 each)
Sieve vibrators
Sieve tippers/spankers
Vibrating gravel chute
Gravel bin & dump mechanism
Vibrating sand chute
Sand bin & dump mechanism
2 active/passive vibration isolation systems (above and below sieve section)
Magnetic separator with permanent and electromagnets
Feedstock bin & dump mechanism
Gangue bin & dump mechanism
Status sensors, including: flow, fill, obstruction, temperature, strain, position, acceleration
Power regulation system
Power, data and control cabling
Coordinating task processor/memory

Table 3-3   *Detailed reliability analysis required an element subsystem list.*

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Control systems:
Tool activation
Crowd-hopper lift and dump
Beneficiator activation
Bin dump: hold-up, rock, gravel, sand, feedstock, gangue
Sieve cleaning
Magnetic separator cleaning

Motor count:
Ground-preparation actuator
Cutting tool actuator
2 redundant crowd-hopper lift
6 bin dump
12 sieve vibrating
12 sieve tipping
12 sieve spanking
2 chute vibrating
Equipment-everting, to facilitate maintenance

HABITAT SYSTEM

Major subsystems:

Shelter footings
Footing tension ties
Inner shelter tunnel end sections
Inner shelter tunnel joint sections
Inner shelter apex plugs
Outer shelter panels
Rivets

Module footings & cradles
Habitat module (all pressurized modules taken as integrated systems)
Connecting node module
Workshop module
Logistics modules (temporarily attached)
2 airlocks
Cupola & tunnel

3 radiator modules
Radiator sunshade
Thermal fluid lines, pump and heat exchanger
Power lines
Local and spacelink communication transceivers
Data and command signal lines
Utility feedthrough connectors
Protective covers for ground-deployed lines
Local lights
Status sensors, including: radiation, strain, position, temperature, pressure, light
Distributed control processors for all components

3 PV arrays
6 PV tracking motors
2 PV control units
RFC module (taken as integrated system)

OXYGEN REACTOR (3 in reference)

Major subsystems for each reactor:
Integrated pressure vessel, including: refractory liner, external MLI, sealing hatch
2 gimbal pivots
R & P tipping mechanism with motor
Oxygen vapor line to reactor field manifold, with connectors
Oxygen vapor manifold (one per field)
Protective covers for ground-deployed lines
2 high-pressure hydrogen storage bottles
Hydrogen delivery lines, with connectors
Hydrogen compressor
Hydrogen heater
Main circulating pump
2 cyclone separators (no moving parts)
Zirconia electrolyzer
Control valves
Relief valves
Power, data and command signal lines, with connectors
Status sensors, including: level, flow, pressure, temperature, acceleration, position
Telemetry transceivers
Navigation beacons
Coordinating task processor/memory
Distributed controllers for all components

7 PV arrays
14 2x-redundant PV tracking motors
7 PV control units
Power regulating substation (taken as integrated unit)
RFC module (taken as integrated unit)

Rails for slag-hopper carts (one per field)
3 slag-hopper carts with motors (per field, one redundant)
Hoppers (used to fill and empty reactors) (22 in reference for entire base)

LLOX DEPOT

Major subsystems:
2 storage tanks, including: MLI, VCS, meteoroid/debris shields, low-absorptivity coating
2 tank support structures, including footings
3 liquefaction/refrigeration units (taken as sealed, integrated systems)
Vapor feed lines (oxygen from reactor field)
Liquid fill/vapor return lines (to buried LLOX terminal)
Connecting fluid/vapor lines and manifolds (between & among tanks & refrigeration units)
Protective covers for ground-deployed lines
2 redundant, cryogenic lander tanking pumps
Control valves
Relief valves
Buried LLOX terminal (under landing pad)
5 radiator modules
Radiator sunshade
Thermal fluid lines, pumps and heat exchangers
Status sensors, including: fluid level, flow, pressure, temperature in all tanks, units & lines
Telemetry transceivers
Navigation beacons
Coordinating task processing/memory
Distributed control processors for all components

The most power is required for initial liquefaction, and comes from PV units offloaded from supplying the steady-state oxygen reactors.

RFC MODULE (2 in reference)

Major subsystems:
Chassis
2 hydrogen gas storage bottles
Oxygen gas storage bottle
Water holding tank
Water pump
2 electrolyzers
4 fuel cells
2 radiator panels (hinged unit covers)
Flexible thermal fluid lines and pump
Power conditioning equipment
Power, data and command signal cabling
External cable connectors
Status sensors, including: flow, fill, temperature, pressure
Navigation beacons
Communications transceivers
Coordinating task processor/memory
Distributed control processors for all components

Table 3-3   *(Continued)*

our subsystem lists, and used to model them. Where necessary, the matchup was done at the component level, and component numbers were estimated.

3) **Normalize the failure rate data collected from a variety of sources to make it comparable.** The available reliability data have been collected in many different environments. The "switch" was chosen as a representative electro-mechanical component, and available data on switch reliability in several different environments was used to develop numerical factors to normalize the different reliability values to one environment. These factors could then be applied to reliability data for other components in other environments, to generate comparable reliability values for all relevant components in a single environment. The standard environment chosen was the "airborne uninhabited fighter" (AUF). This refers to portions of fighter jets not within the environmentally conditioned cockpit, and was chosen because its combination of low pressure, contamination, vibration and temperature extremes seemed a good initial "fit" for the A & R lunar environment. To model our components, reliability data were taken from the "spaceflight" (SF), "airborne inhabited fighter" (AIF), "airborne uninhabited transport" (AUT), "ground fixed" (GF), and "ground mobile" (GM) environments. Normalizing factors were required to translate all these data to the AUF environment. These factors are presented in Figure 3-19.

MIL-HDBK-217E TABLE 5.1.11.4-1 ENVIRONMENT FACTORS FOR SWITCHES		NORMALIZING SWITCH FACTORS TO THE A_{UF} ENVIRONMENT - TO BE USED FOR LUNAR FACTORS	
Space, Flight	$S_F = 1$	$S_F = 25/1 = 25$	
Airborne, Inhabited Fighter	$A_{IF} = 20$	$A_{IF} = 25/20 = 1.25$	
Airborne, Uninhabited Transport	$A_{UT} = 10$	$A_{UT} = 25/10 = 2.5$	
Ground, Fixed	$G_F = 2.9$	$G_F = 25/2.9 = 8.62$	
Ground, Mobile	$G_M = 14$	$G_M = 25/14 = 1.785$	
Airborne, Uninhabited Fighter	$A_{UF} = 25$	$A_{UF} = 25/25 = 1$	

A_{UF} IS THE COMMON NUMERATOR

Figure 3-19   *Normalizing factors allow the use of reliability source data collected in different environments.*

4) **Develop penalty factors to account for differences between the lunar and normalized terrestrial environments.** Although it appeared most appropriate, the AUF environment is different from the lunar environment, and those discrepancies must be compensated. In general, the problems introduced by vacuum, temperature fluctuations, radiation, dust and particle impacts would be more severe on the Moon, while the vibration environment would be less severe. Penalty factors were assigned for the different cases of electronic and mechanical equipment, both mobile and fixed. Electronic components are particularly sensitive to high temperatures. A matrix showing these penalty factors is presented in Figure 3-20. The values chosen are preliminary, and we anticipate future refinement. In particular, these values assumed isolation from dust contamination (which as explained in section 3.7 is probably impractical for many components), and ignored the tribological complications of hard vacuum.

5) **Apply the modification factors to generate mean-time-between-failure (MTBF) estimates for the reference lunar base element designs.** The failure rate (measured in occurrences/10^6 hr) for each chosen model component was burdened by

LUNAR ENVIRONMENTAL STRESS FACTORS COMPARED TO AUF* AS A BASE	RATIONALE & COMMENTS	ELECTRONIC EQUIPMENT				MECHANICAL EQUIPMENT			
		MOVING	FACTOR	FIXED	FACTOR	MOVING	FACTOR	FIXED	FACTOR
Temperature Extremes + 111°C to (-) 171°C	Design to large temp extremes: moving equip. is exposed	Very Large	2.0	Very Large	1.25	Very Large	1.25	Very Large	1.25
Dust ... Contamination	Assume equipment sealed & contained	Same	1.0	Same	1.0	High	1.1	Low to High	1.0
Radiation	Stronger than on Earth	Medium	1.1	Medium	1.1	Medium	1.1	Medium	1.1
Micro Meteor	Could be high, for equipment exposed electronics is protected	Same	1.0	Same	1.0	High	1.1	High	1.1
Vibration	Moving mining equipment and robots have more vibration	Medium	1.1	Low	0.6	High	1.0	Low	0.6
Vacuum	Heat has to be radiated to space	No Change	1.0	No Change	1.0	No Change	1.0	No Change	1.0
Lunar Factor (Product of all stress factors)		2.4 Moving Electronic		0.8 Fixed Electronic		1.6 Moving Mechanical		0.9 Fixed Mechanical	

* Airborne Uninhabited Fighter

/

Figure 3-20 Penalty factors adapted the available reliability data to model the lunar environment.

the normalization and penalty factors just described, then multiplied by the number of such components in each element, and an estimate of the duty cycle for that component. (Reliability data for items like valves were assumed to refer to total elapsed time, whereas data for items like pumps were assumed to refer to actual operation time). Failure rates are additive, so the transformed failure rates for all components modeled in the element were added together. This yielded the element systemic failure rate; its reciprocal then yields the MTBF in hours of actual use for each base element. A worked example of the process is shown in Figure 3-21 for the boom-elevation ring gear of the truck. (This example calculation yields the MTBF for the ring gear in terms of actual hours of component usage rather than total elapsed time; in this case the latter is much larger). Table 3-4 lists the source data, environmental factors, occurrences and calculated failure rates for the major components of the base elements analyzed. Figure 3-22 presents concisely the numerical MTBF results for these elements. For reference, there are 8760 hr in a year.

- GENERIC SOURCE: RELIABILITY ANALYSIS CENTER PUBLICATION NPRD-3, PAGE 211.
- FAILURE RATE FOR A GEAR ASSEMBLY: 32.258 FAILURES PER MILLION HOURS IN A GROUND MOBILE (GM) ENVIRONMENT.
- NORMALIZING GM TO AIRBORNE UNINHABITED FIGHTER (AUF).
  - AUF ENVIRONMENT ASSUMED MOST SIMILAR TO LUNAR ENVIRONMENT
  - ELECTRO-MECHANICAL SWITCH FACTORS IN MIL-HDBK-217E ASSUMED ACCURATE
  - RATIO OF AUF TO GM, IS 25/14 = 1.785.
- NORMALIZING AUF TO LUNAR FACTOR
  - TRUCK IS A MOVING ITEM. THE GEAR IS MECHANICAL. CHOOSE MOVING MECHANICAL = 1.6 AS THE LUNAR FACTOR.
  - PERFORM CALCULATION - LUNAR FAILURE RATE

    [GENERIC 32.258 FAILURES PER 10^6 HOURS] TIMES [AUF/GM 1.785 RATIO] TIMES [LUNAR FACTOR 1.6] = 92.129 FAILURES PER 10^6 HOURS.

Figure 3-21   *The worked example of truck-boom ring-gear reliability illustrates the calculation technique.*

Several conclusions emerged:

1)   **Lunar equipment reliability appears to be an achievable goal, but conscientious maintenance will be a major activity.**   R & R will be an ongoing task during every lunar cycle. Detailed lunar equipment reliability studies are needed to formulate early requirement identification, and support system engineering analysis. Developing better models for performing such reliability studies is a prime candidate for future work.

2)   The numerical results are probably most useful for comparative purposes with each other, although we expect that they capture the scale of the lunar reliability problem. With more complete component detailing, and more accurate part counts, we can expect the calculated failure rates to rise. **The failure rates calculated do not contradict our presumed overall spares provisioning of 15 % of the equipment's active component mass.**

3)   When folded together, including overall numbers and daytime/nighttime duty cycles of all base elements analyzed, the preliminary calculated rates result in a grand total lunar base MTBF of 58 hr, or about 12 failures per lunar daytime period. When all components (and all elements) are accounted for, we would expect this to approach the currently achievable manned space system failure rate of around 5 per 24 hr period (70 per lunar daytime). Again, these failures are counted regardless of severity.

4)   The miner MTBF is of the same order as that for the vehicles, which we would expect since it also operates directly in and on the regolith.

5)   The RFC module MTBF is much less than that for the other fixed elements. Historically, fuel cells have proved to be rather cantankerous, so this result is not surprising. Accommodating regular maintenance activity then becomes an overriding design constraint. Figure 3-23 describes some design recommendations for fuel cells, which address this expectation.

6)   The oxygen reactor reliability may be less than as shown, due to degradation of the brittle refractory liner by batch thermal-cycling. Periodic recoating using a specialized plasma-sputtering tool may allow _in situ_ refurbishment.

7)   The PV units have by far the greatest MTBF, as expected.

8)   Thermal design considerations are especially important. Simple, robust techniques for rejecting waste heat under lunar surface conditions will be essential for electronic components, power storage devices and motors.

STRADDLER - MAJOR ITEMS

	GENERIC FAILURE RATE F/10^6	ENVR FACTOR	LUNAR FACTOR MOVING	QTY	DUTY CYCLE	LUNAR FAILURE RATE F/10^6
AXLES	2.836	AIF	Mech.	3	1.0	17.016
WHEELS	1.272.264	AUF	*	3	1.0	3.816.792
BRAKES	4.273	GF	Mech.	3	0.1	17.680
CONTROL SYSTEM	0.485	GF	Elect	10	1.0	100.337
DC MOTORS	4.716	GF	Elect	34	0.8	2.653.757
ROBOTIC ARMS	54.182	GF	Elect	2	1.0	2.241.834
GUIDANCE SYSTEM	2.427	GF	Elect	1	1.0	50.210
COMMUNICATION SYSTEM	1.941	GF	Elect	1	1.0	40.155
SET OF LOCAL LIGHTS	0.625	SF	Elect	1	0.1	3.750
ANTENNA	0.010	SF	Elect	1	1.0	0.600
OPTICAL SENSORS	2.976	GF	Elect	4	1.0	246.270
COMPUTER	2.427	GF	Elect	1	1.0	50.210
SOLAR ARRAY	3.333	SF	Elect	6	1.0	1.199.880
BATTERY PACK	0.166	SF	Elect	3	1.0	29.880
SET OF CABLES - INCLUDES POWER	0.125	SF	Elect	3	1.0	22.500
LEVEL SENSOR	2.976	GF	Mech.	3	1.0	123.135
FIXED HOISTS	98.232	AUF	Mech.	9	0.5	707.270
CORNER PINION WITH JACKS	9.259	AUT	Mech.	6	1.0	222.216
				Total λ		11.543.492

```
MTBF  =  1/λ          =   86.6   hours, with wheels
MTBF  =  1/7.726.7    =  129.4   hours w/o wheels
MTBF  =  1/7.876.7    =  127.0   hours target reliability w/ wheels
where each wheel      =   50     failure/10^6 hrs, target failure rate
```

* Design incorporates lunar factor

TRUCK - MAJOR ITEMS

	GENERIC FAILURE RATE F/10^6	ENVR FACTOR	LUNAR FACTOR MOVING	QTY	DUTY CYCLE	LUNAR FAILURE RATE F/10^6
AXLES	2.836	AIF	Mech.	2	1.0	11.344
WHEELS	21.281.123	AUF	*	4	1.0	85.124.492
BRAKES	4.273	GF	Mech.	4	0.1	23.573
CONTROL SYSTEM	0.485	GF	Elect	12	1.0	120.404
DC MOTORS	4.716	GF	Elect	10	0.8	780.517
ROBOTIC ARMS	54.182	GF	Elect	1	0.5	560.459
GUIDANCE SYSTEM	2.427	GF	Elect	1	1.0	50.210
COMMUNICATION SYSTEM	1.942	GF	Elect	1	1.0	40.176
SET OF LOCAL LIGHTS	0.625	SF	Elect	1	1.0	37.500
ANTENNA	0.010	SF	Elect	1	1.0	0.600
SET OF BEACON OPTICAL SENSORS	2.976	GF	Elect	1	1.0	61.567
COMPUTER	2.427	GF	Elect	1	1.0	50.210
BATTERY PACK	0.166	SF	Elect	1	1.0	9.960
SET OF CABLES	0.125	SF	Elect	1	1.0	7.500
LEVEL SENSOR	2.976	GF	Elect	1	1.0	61.567
TELESCOPE BOOM	0.686	SF	Mech.	1	1.0	26.640
OUTRIGGERS	0.686	SF	Mech.	4	0.5	53.280
PINION DRIVE	0.259	AUT	Mech.	1	0.5	3.626
RING GEAR FOR THE BOOM	32.258	GM	Mech.	1	1.0	184.258
				Total λ		87.207.883

```
MTBF  =  1/λ            =   11.5   hours, with wheels
MTBF  =  1/2.083.391    =  480.0   hours w/o wheels
MTBF  =  1/2.283.391    =  437.9   hours target reliability w/ wheels
where each wheel        =   50     failure/10^6 hrs, target failure rate
```

* Design incorporated lunar factor

Table 3-4 *The reliability of each base element is derived from subsystem performance.*

ROVER · MAJOR ITEMS

	GENERIC FAILURE RATE F/10^6	ENVR. FACTOR	LUNAR FACTOR MOVING	QTY	DUTY CYCLE	LUNAR FAILURE RATE F/10^6
AXLES	2.836	A$_{IF}$	Mech.	2	1.0	11.344
WHEELS	63.856.960	A$_{UF}$	*	4	1.0	255.427.840
BRAKES	4.273	G$_F$	Mech.	4	0.1	31.431
CONTROL SYSTEM	0.485	G$_F$	Elect.	11	1.0	110.370
DC MOTORS	4.716	G$_F$	Elect.	9	0.8	710.747
ROBOTIC ARMS	54.182	G$_F$	Elect.	1	0.2	224.182
GUIDANCE SYSTEM	2.427	G$_F$	Elect.	1	1.0	50.210
COMMUNICATION SYSTEM	1.941	G$_F$	Elect.	1	1.0	40.176
SET OF LOCAL LIGHTS	0.625	S$_F$	Elect.	1	1.0	37.500
ANTENNA	0.010	S$_F$	Elect.	1	1.0	0.600
SET OF BEACON OPTICAL SENSORS	2.976	G$_F$	Elect.	1	1.0	61.567
COMPUTER	2.427	G$_F$	Elect.	1	1.0	50.210
SOLAR ARRAY	3.333	S$_F$	Elect.	1	1.0	199.980
BATTERY PACK	0.166	S$_F$	Elect.	1	1.0	9.950
SET OF CABLES	0.125	S$_F$	Elect.	1	1.0	7.500
					Total λ	256.973.618

```
MTBF  =  1/λ = 1/256,973,618 =   3.9 hours. with wheels
MTBF  =  1/1,545.778        =   646.9 hours w/o wheels
MTBF  =  1/1,745.778        =   572.8 hours target reliability w/ wheels
          Where each wheel  =   50 failure/10⁶ hr. target failure rate.
```

* Design incorporated lunar factor

FACILITY · FUEL CELL MODULE

	GENERIC FAILURE RATE F/10^6	ENVR. FACTOR	LUNAR FACTOR FIXED	QTY	DUTY CYCLE	LUNAR FAILURE RATE F/10^6
H$_2$ TANK	1.615	G$_F$	Mech.	2	1.0	25.058
O$_2$ TANK	1.615	G$_F$	Mech.	1	1.0	12.529
PUMP	154.535	A$_{UT}$	Mech.	1	1.0	347.704
VALVE	1.714	G$_M$	Mech.	10	1.0	27.535
ELECTROYZER	1.630	G$_F$	Mech.	2	0.5	12.646
FUEL CELL	12.123	S$_F$	Elect.	4	0.5	484.920
CONTROL	0.485	G$_F$	Elect.	1	1.0	3.345
RADIATOR	59.880	A$_{UF}$	Mech.	2	1.0	107.784
CABLE SET	0.125	S$_F$	Elect.	2	1.0	5.000
					Total λ	1.026.521

MTBF = 1/λ = 974.2 hours

FACILITY · SOLAR PANEL ARRAY

	GENERIC FAILURE RATE F/10^6	ENVR. FACTOR	LUNAR FACTOR FIXED	QTY	DUTY CYCLE	LUNAR FAILURE RATE F/10^6
SOLAR ARRAY	3.333	S$_F$	Elect.	1	1.0	66.660
CONTROLLER	0.485	G$_F$	Elect.	1	1.0	3.345
TRACKING MOTOR	4.716	G$_F$	Elect.	2	1.0	65.043
CABLE SET	0.125	S$_F$	Elect.	1	1.0	2.500
CONNECTOR	0.0232	S$_F$	Mech.	1	1.0	0.522
					Total λ	138.070

MTBF = 1/λ = 7,242.7 hours

Table 3-4   (Continued)

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FACILITY - LOX STORAGE PLANT

	GENERIC FAILURE RATE F/10^6	ENVR FACTOR	LUNAR FACTOR FIXED	QTY	DUTY CYCLE	LUNAR FAILURE RATE F/10^6
REFRIGERATOR	25.000	G$_F$	Mech.	2	1.0	387.900
STORAGE TANK	1.615	G$_F$	Mech.	2	1.0	25.058
RADIATOR	59.880	A$_{UF}$	Mech.	1	1.0	53.892
CONTROL VALVE	1.714	G$_M$	Mech.	6	1.0	16.521
FLUID/GAS LINE	0.100	S$_F$	Mech.	6	1.0	13.500
CRYO PUMP	154.535	A$_{UT}$	Mech.	1	.02	6.954
CONTROL	0.485	G$_F$	Elect.	19	1.0	63.547
SENSOR	2.976	G$_F$	Elect.	11	1.0	225.747
COMPUTER	2.427	G$_F$	Elect.	1	1.0	16.737
					Total λ	809.856

MTBF = 1/λ = 1,234.8 hours

FACILITY - LOX REACTOR PLANT

	GENERIC FAILURE RATE F/10^6	ENVR FACTOR	LUNAR FACTOR FIXED	QTY	DUTY CYCLE	LUNAR FAILURE RATE F/10^6
HEATER, H$_2$	1.000	S$_F$	Elect.	1	1.0	20.000
PRESSURE VESSEL	1.615	G$_F$	Mech.	1	1.0	12.529
SEAL	3.495	G$_M$	Mech.	1	1.0	5.615
BLOWER	2.400	S$_F$	Elect.	1	1.0	48.000
COMPRESSOR	5.959	G$_M$	Mech.	1	0.5	4.787
H$_2$ TANK	1.615	G$_F$	Mech.	2	1.0	25.058
ELECTROLYZER	1.630	S$_F$	Elect.	1	0.5	16.300
CONTROL	0.485	G$_F$	Elect.	7	1.0	23.412
COMPUTER	2.427	G$_F$	Elect.	1	1.0	16.737
SET OF CABLES	0.125	S$_F$	Elect.	2	1.0	5.000
					Total λ	177.438

MTBF = 1/λ = 5,635.8 hours

FACILITY - MINING PACKAGE

	GENERIC FAILURE RATE F/10^6	ENVR FACTOR	LUNAR FACTOR FIXED	QTY	DUTY CYCLE	LUNAR FAILURE RATE F/10^6
COMPUTER	2.427	G$_F$	Elect.	1	1.0	50.210
VIBRATING SIEVES	0.500	S$_F$	Elect.	12	1.0	120.000
MAG. SEPARATOR	0.030	S$_F$	Elect.	1	1.0	0.600
MOTOR	4.716	G$_F$	Elect.	40	.05	65.043
ACTUATOR	40.292	A$_{UT}$	Elect.	2	1.0	161.168
DUMP MECHANISM	1.630	G$_F$	Mech.	6	0.1	7.587
CONTROL	0.485	G$_F$	Elect.	9	1.0	30.101
SENSORS	2.976	G$_F$	Elect.	30	1.0	615.675
					Total λ	1,050.384

MTBF = 1/λ = 952.0 hours

Table 3-4   *(Continued)*

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```
                            ┌─────────┐
                            │ ROBOTS  │
                            └────┬────┘
          ┌──────────────────────┼──────────────────────┐
     ┌─────────┐           ┌───────────┐          ┌───────────┐
     │  ROVER  │           │ OUTRIGGER │          │ STRADDLER │
     │ (Jeep)  │           │  (Truck)  │          │           │
     └─────────┘           └───────────┘          └───────────┘
```

MTBF =   3.9 Hours W/Wheels   11.5 Hours   86.6 Hours

MTBF = 646.9 Hours W/O Wheels   480.0 Hours   129.4 Hours

Reliability Goal with Wheels
MTBF = 572.8 Hours W/Wheels   437.9 Hours   127.0 Hours

```
                            ┌───────────┐
                            │ FACILITIES│
                            └─────┬─────┘
    ┌──────────┬──────────┬───────┼────────┬──────────┬──────────┐
┌────────┐ ┌─────────┐ ┌────────┐ ┌──────────┐ ┌──────────┐ ┌────────┐
│ SOLAR  │ │FUEL CELL│ │  LOX   │ │   LOX    │ │ MINING   │ │HABITAT │
│ ARRAYS │ │   S/S   │ │REACTORS│ │ STORAGE  │ │  PKG     │ │        │
└────────┘ └─────────┘ └────────┘ └──────────┘ └──────────┘ └────────┘
```

MTBF = 7,242.7 Hours   974.2 Hours   5,635.8 Hours   1,234.8 Hours   952.0 Hours   N/A
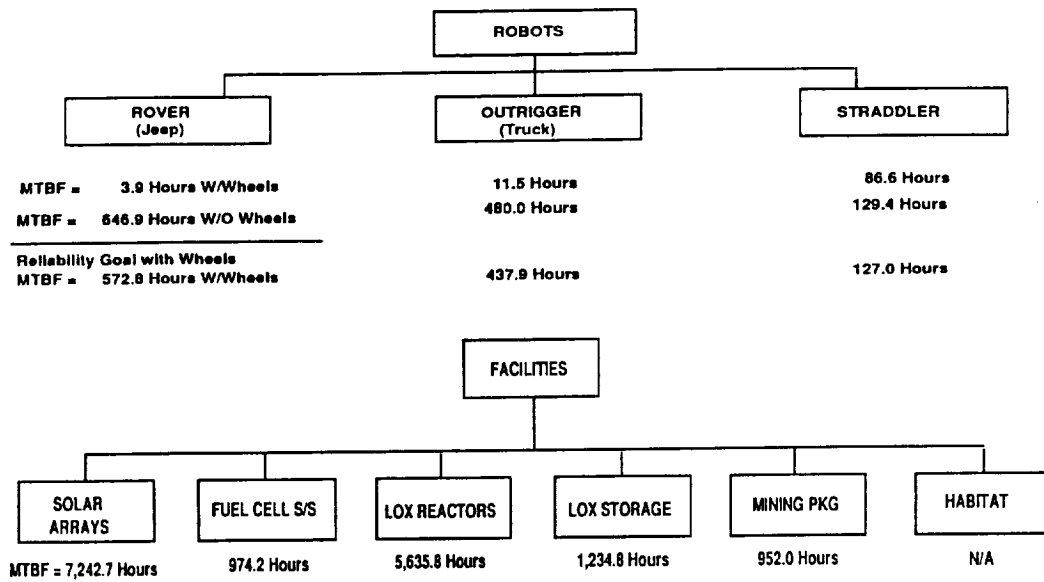
Figure 3-22 *The expected reliability of various base elements can be compared directly.*

Available   Needed

STS Fuel Cell

-- Component - replaceable

-- Environmental countermeasures

-- Accept slight mass penalty (10 %) and substantial volume penalty (300 %) to increase external access surface area

-- Accommodate in - line, single - motion actuation

-- Use common, captive fasteners

-- Avoid nested, cascading changeout paths

-- Instrument for handshaking, functional self - test

-- Unit - replaceable

-- 0.35 x 0.38 x 1.01 m ; 91 kg
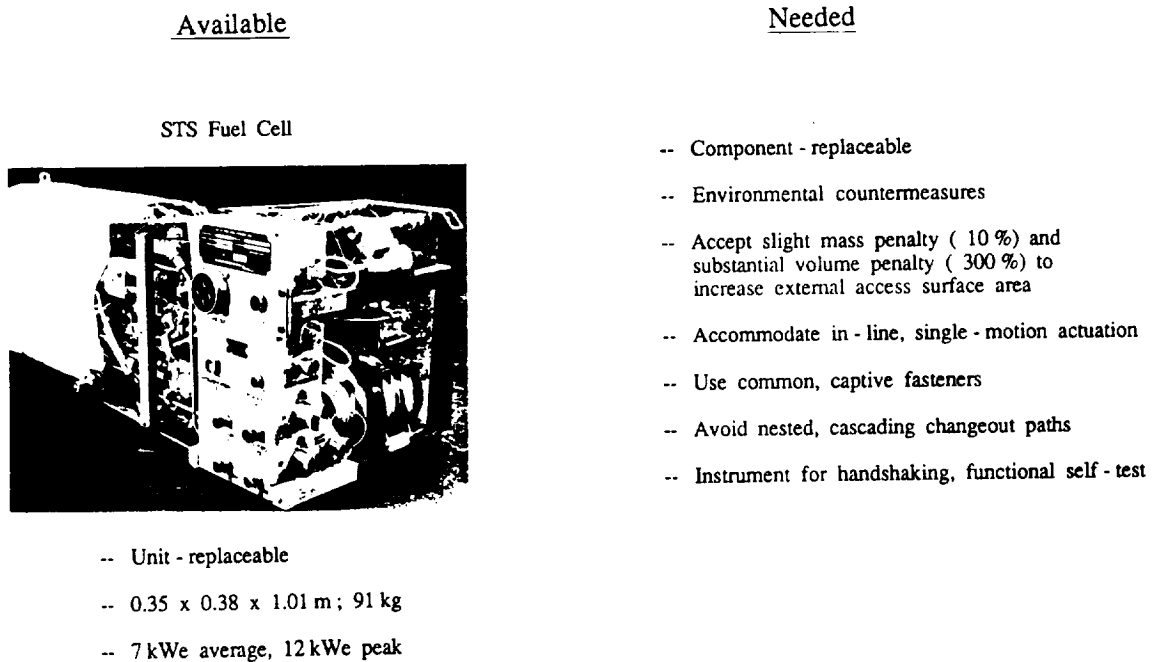
-- 7 kWe average, 12 kWe peak

Figure 3-23 *Designing complex space equipment for repair introduces new constraints.*

9)   All-metal wheels need to be developed that can last a long time in the lunar environment. The LRV wheels were designed for a total life of only a few hours, so that simply adopting those data for our mobile robots would yield extremely poor system reliability. Our larger wheels fare better because they turn fewer times per kilometer traveled. Our response, for the purpose of this analysis, was to reverse the problem; we specify the MTBF (of order 20,000 hr) that would be required of the wheels to make their failure rates commensurate with other vehicle components. The separate results (with LRV-technology wheels; without wheels included; and with target-reliability wheels included) are all shown for each mobile vehicle in Figure 3-22.

3.9   SPARES AND LOGISTICS ANALYSIS

An adequate supply of the right types of spares could spell the difference between smooth functioning and severe interruptions for a robotically operated lunar base. No operations scenario is complete without attention to the parts required to keep it going. Replacement components must come from Earth, at a transportation cost roughly six times as great as that required to supply them to SSF.

A generic spares-provisioning analysis was conducted and reported in our "Orbital Assembly Study". The details will not be repeated here, because they are particular to interplanetary space transportation vehicles. Abstracted however, the fundamental results are instructive for lunar base spares provisioning. Assume an integrated space system comprised of 10,000 distinct Class S (120,000 hrs MTBF) components, and expected to complete a 20,000 hr (2.3 yr) mission with a 99 % probability of everything still working by the end. Assume further that a failure is defined as the off-nominal performance of a component (regardless of severity), and that the occurrence of failures can be modeled by a Poisson distribution. If in situ R & R is available at the component level (circuit cards, valves), and if the components share at least 100x commonality (the system uses 100 of each component), then 1/3 as many dormant, available spares are required as active components. This can be a substantial mass burden for a space system. If 100x commonality is not achieved (a likely case), or when the real MTBF ratio of dormant-to-active active components (which is about 30) is considered, the spares ratio becomes worse.

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On the other hand, if subcomponent R & R is permitted (replacing failed chips or valve seals, for instance), or if the mission can be designed to be successful without all its parts functioning nominally, the required spares ratio gets better. Some degree of both approaches can be expected to characterize a real lunar base, and are baselined into our operations scenario. In a system of diverse elements and functions like a habitable, industrial lunar base, the lower the level of part changeout, the more opportunity for commonality. Having crew available (intermittently at first, and eventually full-time) to perform real (subcomponent) repairs on faulty components introduces tremendous flexibility in the response to failures. In many cases, human cleverness and adaptability can prevent otherwise inconsequential failures from propagating throughout the system, thus obviating the "brute force" approach of providing enormous numbers of spare components. With human crews responding to contingencies, more repair options become available. And specifying internally redundant systems (3 refrigerator units when only 2 are needed at once; 3 oxygen reactors; 21 PV arrays, each with two tracking motors; identical pairs of all mobile robots; multiple methods to accomplish tasks) allows overall performance to continue or degrade gracefully until deferred repairs can be accomplished. This reduces the issue of "mission failure" largely to one of "mission efficiency", a key transition for all long-term operations. Failure management then becomes a controllable operation. A wider range of operation modes, and parallel paths to task completion, becomes possible.

This layered philosophy of operational robustness for integrated systems still requires spare parts, of course. Because of the inevitable uniqueness of many components in a modest, initial lunar base, we favor spares provisioning at half the theoretical value explained above, or 1/6 the active component mass. The results of the reliability analysis presented in section 3.8 give no cause to challenge this 15 % allocation as a useful reference for preliminary systems studies. The manifests detailed in section 3.2 show that we have budgeted spares at over 6 % of total lunar base hardware mass. Verification of this proportion as appropriate would require a detailed study of which parts to take and in what numbers, a level of detail beyond the scope of this study. However, the implication that 40 % of the base mass is comprised of active components (as opposed to structure or other inerts) is probably conservative.

The location of spares depots is an important consideration. For this study, we have assumed that our entire spares budget should be located at the lunar base, immediately

available to the robots and crew. However, a more detailed analysis to determine the criticality of each spare part could allow other options. Early in the buildup of a lunar base, the consequence of some failures would be only a delay. So if the situation could be stabilized via supervision from Earth, the proper spares could be manifested onto the next scheduled flight. This operations mode would avoid the mass penalty of delivering many spares to the base, many of which might remain unused for a long time. Other depot possibilities include the transportation node at SSF, stockpiling at KSC ready for launch from Earth, and even manufacture-on-demand. In keeping with our goal of operational robustness, we can reasonably expect the base to exploit the full spectrum of depot options, based on a part-by-part criticality analysis and risk/manifesting tradeoff.

Some base elements -- notably the miner and main habitat module -- have no backup units as do the vehicles, oxygen plant and power plants. The miner in particular introduces a pinch point in base operational reliability; without the gravel and sand that it generates, all permanent base construction shuts down. Thus, its components that are prone to failure are high-priority spares items. This probably should include the more vulnerable structural parts as well, because of both the importance of the miner and its rough operating environment. In addition, another complete miner unit would be among the first equipment delivered after the nominal buildup period (after the 15th flight). The miner seemed intrinsically less vulnerable to breakdown than the mobile robots (the MTBF figures in section 3.8 confirm this), so we deferred manifesting its backup until the base growth phase.

3.10 EQUIPMENT AND OPERATIONS SYNERGIES

The systems we developed for the reference lunar base scenario were evolved along with specific performance requirements, based on our groundrules, assumptions, and task analysis. However, having been iterated in an effort to optimize them for our purposes, some of the elements have attained versatility beyond our limited scenario. For early planetary activities, in fact, the novel, unplanned or secondary uses to which equipment can be put will be an important criterion for judging success in an ongoing, cost-

conscious exploration program. Much of the equipment we have described in this report could be used, as available, to extend the reach of humans away from a core lunar base, enlarging their theater of surface operations. Once a planetary foothold is gained, productive forays will become easier, and the cost of more extensive investigations will become marginal. Potential secondary activities would be: performing geological exploration; setting up other remote research facilities (for astronomy, astrophysics and lunar environmental science), and establishing satellite outposts and secondary bases.

Some very large science instruments (extremely large radio dishes on Farside, for example) would be beyond the scale of our initial mobile robots. However, the straddler would prove a particularly versatile tool for installing and constructing science mission systems. For instance, its large size, mass, and carrying capacity, and its maneuverability and autonomy would serve well for a mobile drilling platform. With special-purpose equipment (down-hole motor, down-hole packer bit-loading mechanism), 7 cm cores and lateral drilling at depths of several hundred meters could be accomplished. The straddler's self-leveling locomotion and slow speed, and ability to offload itself from a lander, could open up rough (and scientifically important) terrain to investigation planetwide. Locally, its carrying capacity would be useful for transporting and emplacing complete safe-haven outposts in regions surrounding the core base. Such outpost modules may be fairly simple to outfit at the core base, as logistics modules are continually brought to the base and emptied.

The truck could be used to resupply outposts with consumables and spares. Additional, special-purpose trailers for the truck could greatly facilitate telepresent and manned investigations into pure and applied science in the plains and hills around the equatorial Mare Tranquillitatis site. The truck chassis itself, less the high-reach boom, could be outfitted with a standard (spacecraft) crew cab and ancillary equipment to make a pressurized rover. Such a vehicle could sustain people for week-long sorties (and would not require a separate hardware procurement program). With a larger modular cabin, and by towing provisions trailers including a cryogenic RFC power system, the same basic vehicle could support even longer trips. Excursions spanning a full lunar cycle could open up to direct human exploration a region as large as 3000 km across (almost 20 % of the Moon's total surface area) centered on the base.

The mining and processing activities baselined into the reference concept provide large quantities of two kinds of semi-processed native regolith not used by our limited scenario: ilmenite-deficient gangue smaller than 0.5 mm, and reactor "slag" rich in admixed elemental iron and rutile. Processes to use these and other native materials could be investigated in situ as early as the second crew visit in our scenario. The gangue may prove to be a valuable feedstock for processes yielding cast-basalt or glass-based materials for structural components, shielding and architectural elements, and sintered paving blocks. The slag may prove particularly valuable as a ready-made iron alloy for tool and part manufacture using hot isostatic pressing (HIP) or other methods. Certainly, studies of the engineering properties and processing of materials made available by primary base activities would be an important task for onsite crews.

3.11 BASE GROWTH

A nascent feature of current space exploration concepts is their indefinite extension into the future. A goal of the U.S. National Space Policy is to expand human presence into the solar system. Considering exploration initiatives which aspire toward that goal as milestones, rather than finite programs, introduces a real need to project concept designs beyond their initial performance. We have limited the quantitative analysis of our reference scenario to a period spanning just the four years it takes to emplace the base elements and get them running at nominal capacity. Projecting our scenario beyond those first four years of buildup and operation requires looking at two different time scales: the immediate and the distant.

IMMEDIATE AND SHORT-TERM GROWTH - The most immediate equipment addition to the base would be a backup miner unit, since as discussed already this device represents an operational choke point. Delivery might even occur before a third manned visit. Subsequent to those two events however, we would complete the sitework (already begun to generate gravel) on two more landing pads in the spaceport. Having three operable pads, each complete with debris protection, lander conditioning utilities and LLOX depots, would allow simultaneous lander visits and servicing, and broaden contingency options.

Next, growth would concentrate on **enhancing operations efficiency and extent**. This would be facilitated by supporting human crews of 4 - 6 for periods of up to 6 months, requiring the ability to abort back to Earth within days. Specific growth accommodations for this phase would involve:

1)   Adding another habitation module, with commensurate growth in its PV and RFC power sources, and safe haven capability for 2 - 4 wk periods. This may include compartmentalization such that the safe-haven volume requiring conditioning is small.

2)   Adding more power storage for nighttime activity, particularly to charge certain vehicles. The system must be flexible enough to accomplish work at night as desirable, after the day-only mode has bootstrapped the base.

3)   Installing better facilities for crew involvement as onsite supervisors of robotic activity, and expanding equipment and vehicle maintenance capabilities. As the base and operations mature and as human presence tends toward permanence, onsite repair capabilities will improve and thus maintenance facility requirements will grow. Increasingly more supplies, tools, equipment and space will be needed.

4)   Stocking larger buffers of crew and industrial supplies, and more complete spares inventories; proving more confidence in regular lander logistics supply.

5)   Building additional storage facilities, and using logistics modules for pressurized storage.

6)   Improving methods for cleaning dust and caked regolith off of equipment and suits.

7)   Qualifying support systems (modules, cryogenic storage and filling facilities, landers) for longer surface stay lifetimes.

8)   Introducing methods of providing more power to mobile robots, to enable faster travel and excavation. This includes installing cryogenic RFC systems onboard vehicles.

9)   Refresher training for dynamic flight phases (ascent, rendezvous, dock, Earth capture). Flight crews must always be prepared for the real thing.

10)   Verifying higher levels of automated task control.

        Other industries (recovering volatiles from regolith, sintering paving and shielding blocks from gangue, recovering alloyed metals from reactor slag, making glass fibers from sorted regolith) would be emplaced, and oxygen production increased. The base could begin to support more frequent lander flights, and to supply propellant for transfer vehicles in LLO.

        The next phase would focus on **enabling permanent human presence**. Supporting 12 crew for 2 yr stays (and setting the system performance requirement of a 6 month wait for return to Earth) is a convenient reference point. This phase would require many of the same improvements just listed, plus others, including:

1)   More advanced medical capabilities, additional health maintenance facilities, exercise accommodations, and safe-haven capacity.

2)   Full-time industrial operations, which means adding nuclear power plants. Solar array fields would prudently be retained for backup. Crew operations might productively go to two shifts within each 24 hr period.

3)   More extensive science facilities, with more extensive data gathering, and the ability to explore more widely. Scientific and prospecting expeditions could be sent all over the Moon from an established base.

4)   Outposts away from the main base. Locally, these will accommodate extensive exploration in the vicinity of the base. Farther away, they will permit visits to the same spots, and be the seeds of other bases.

5)   A dependable, regular lander schedule, and logistics supply system.

6)   Closure of the carbon and nitrogen loops (oxygen will be abundant), and food growth. A true CELSS (controlled ecological life support system) would require the addition of dedicated biomass modules. Gardening activities can provide a beneficial and satisfying outlet for crew leisure time.

7)   Improved habitability conditions, including more pressurized volume for living and working, more emphasis on privacy provisions, better esthetics, and better off-duty provisions. As stay times increase, increasingly more attention must be paid to amenities for the crews. This SSF maxim applies equally to planetary surface operations. It will be important to provide resources that support quality leisure time; the resource of greatest importance for overall base planning is pressurized volume. Both private quarters and recreation volume will be needed, as will recreational equipment. Extensive habitat module interior modifications and refurbishment can be expected.

A secure base will be one where human presence is continuous, where logistics and crew exchange are regular and routine, where line and field maintenance are routinely conducted and where the facility is functional and safe in degraded modes. Then, safe havens and escape vehicles would represent survival only after two or three levels of redundancy had been consumed. A major milestone will be the point after which the preferred response to a serious contingency is not to abort to Earth, but to remain onsite and work the problem through. Security would be achieved with roughly a tripling of the physical facilities proposed by this study. **Real self-sufficiency, however, would require much more growth**, ISRU processes much more elaborate and complete than mere oxygen production, and an environmental buffer too large to be practically achieved with linkages of small pressurized modules.

LONG-TERM AND EVENTUAL GROWTH - The Moon will play a variety of roles in evolutionary space development, including acting as a nearby planetary technology testbed, a platform for advanced astronomy, and perhaps as a source of raw materials for propulsion and construction in space, as well as power production on Earth. We next examine briefly how a minimal initial lunar base, having grown to support permanent human occupancy and then extra-Terrestrial self-sufficiency, could finally grow into a major economic node supporting human expansion into the solar system.

The reference site plan (Figure 2-3) is zoned for indefinite base growth, to avoid topological interference of base functions far into its future. Power plants to supply both human and industrial needs would grow outward to the west. This limits degradation of

solar fields by propulsive debris from an enlarging spaceport. But reserving the western region for power generation also means that nuclear reactors can be placed there safely, with only light shielding. The tradeoff between transmission losses and shielding mass depends on the the use of in situ shielding.

Industrial operations would grow to the north, into the rich plains of the Sea of Tranquility. That way, even widespread mining and processing activities can be most proximate, and avoid interfering with other base activities. Should ^{3}He mining come to pass, vast areas of mare soil would need to be processed to meet the projected energy needs of Earth.

The pressurized habitation "village", constrained to be contiguous, could grow unimpeded to the south. If the base continued to grow into a real lunar city, and if sited originally close enough to the highlands at the Sea's edge, we could envision the human quarter eventually spreading into the interesting topography of the foothills there.

Supplying large amounts of lunar products to convenient staging points in space (such as L2) would require a mass-driver or other high-throughput propulsion system. A mass driver would be sited in the spaceport, firing eastward horizontally under the lander approach window. The rest of the spaceport could grow as needed to the east, with the region surrounding and beyond it remaining "wilderness". Preserving untouched lunar terrain within sight of the settlement may well prove critical for psychological relief if the base grows into a densely populated city. In the enclosed, technological human environment of a lunar settlement, looking at barren wilderness would provide the only access to natural order available to the inhabitants. Protecting that visual access may become a dominant site constraint, albeit one easily foreclosed by short-sighted base planning. It makes sense to combine such an exclusion zone with the spaceport, since the latter's function will keep it the most growth-choked base element indefinitely into the future. Regular, economical transportation to a Farside science base could be accomplished with a robotically-built surface rail system heading east around the limb.

Following the zoning scheme proposed here, the Tranquility settlement would develop naturally a cruciform, cardinally-oriented, transportation and utility service infrastructure. Connecting a human community to the south, a robotic industrial complex expanding to the north, power sources to the west, and a spaceport bordering the

wilderness to the east, this cross-axis service armature could grow with the base to enormous scale, long after the initial hab modules, oxygen reactors and solar arrays were recycled and the initial roads were forgotten. The city center would grow into an "activity hub" at the intersection of these cardinal spines. Although evolved directly out of our site constraints, this orthogonal infrastructure is immediately recognizable to city planners as the decumanus, kardo, and forum layout of all Roman cities: one of the most pervasive, persistent and successful designs in the history of human culture. The simplicity of such a sectored scheme evidently serves well the requirements in scale, specific element type, and even program emphasis which change over long timescales in human settlements. Growth would be accommodated incrementally, without necessitating disruptive demolition or expensive replanning, even up through the time when most of the human base inevitably gets built underground. Carefully planned then, even the most modest initial site could thus evolve smoothly into a true lunar settlement.

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4. MARS OPERATIONS

One of the most important benefits of lunar operations is that they can help prepare for Mars operations. Both environments share, to different degrees, many of the same complications: remoteness, lack of infrastructure, temperature extremes, dessicated regolith, low pressure, little foreknowledge and less experience. However, there are important differences, which would result in somewhat different manifestations of robotic operations to establish early bases. The Mars problem deserves detailed study. Here we can only highlight some salient observations.

POWER AND RESOURCE CONSTRAINTS - Mars has a diurnal cycle quite similar to Earth's (period 1.026 d); the diurnal surface temperature variation is between 35 - 50 K, and the surface stays below the freezing point of water. Viking readings varied from 150 K to 250 K, a range much more amenable to component reliability than the Moon's. With a heliocentric semimajor axis of 1.52 AU, Mars receives less than half the solar flux that the Moon does. In addition, its unusually large orbital eccentricity results in a total 39 % seasonal solar flux variation. Solar collectors would need to be much larger to produce the same amount of power in the worst case, but nighttime storage would be far simpler than on the Moon (batteries would suffice for many applications). Mars has an atmosphere, albeit a tenuous (0.007 atm) one of 95 % CO_2, some nitrogen and argon, and trace gases. There are great seasonal pressure variations as CO_2 aternatively freezes out onto each pole. Mars weather is dramatic, with frequent localized dust storms; and occasional, long-lived, global dust storms caused by absorptive thermal feedback between clouds of dust eroded by saltation and seasonal thermal tidal winds. The irregular, but severe and long-lived obscuration that results reduces PV efficiency by as much as 70 %. Options for a continuous Mars base include having a large excess PV power production margin available, or running its industry at reduced levels during dust storms (which can last up to a year). Nuclear power is enhancing for permanent Mars operations.

The two driving requirements for an initial Mars base would be, again, facilitating crew presence and producing oxygen for propellant. The complexion of both of these goals is different on Mars. The radiation environment on Mars is much more benign due to the integrated effect of the gas molecules in its atmosphere. Thus, shielding for habitat modules could be simpler than on the Moon to achieve the same level of protection. Perhaps only a canopy shelter would be required, greatly simplifying base expansion and

vehicular access, and reducing the time and complexity of the sheltering task. And the atmospheric CO_2 provides a much more available source of oxygen than the oxide-rich martian regolith. Consequently a plant to crack the CO_2 into CO and O_2 would be a gas processor, requiring no regolith-moving.

Regolith-moving would still be required for clearing (Viking surface images reveal a great abundance of rocks on the martian plains), road-building, foundation preparation, and perhaps canopy shielding. Hardly anything is known about the engineering mechanics of the martian substrate. Questions of the thermal stability of soils rich in permafrost remain, although near-surface permafrost does not seem likely within 40° of the equator. Certainly, better precursor data than exist now, both about surface roughness and soil properties, will be invaluable for designing equipment concepts for Mars surface operations.

COMMUNICATIONS, AUTONOMY AND REPAIR - Communications between Earth and Mars are complicated by seasonal solar conjunction (the short period each year when the sun is in the way), the need for planet-orbiting relays (to allow continual transmissions as Mars rotates), reduced bandwidth allowance (compared with lunar distances), and frustrating lightspeed delays. Not counting switching delays, the round-trip signal time between Earth and Moon is about 2.5 s. Because Mars is so much farther away, and because its motion in space is independent of Earth's, the round-trip signal time between Mars and Earth varies by a factor of six, between about 8 and 42 min. Thus while, teleoperating lunar robots from Earth is possible with some practice, strict teleoperation of Mars surface robots from Earth is out of the question. For unmanned mission phases, then, **controlling robotic operations at Mars demands the higher-level (supervisory and automated task control) capabilities we have advocated for lunar operations.** The desire for efficiency, versatility and safety no longer drives this choice as it did for the Moon; lack of alternatives does. All mission phases, including aerocapture, rendezvous and docking, descent and touchdown, navigation and manipulation, will call for more true autonomy for planning, execution, obstacle avoidance, error recovery and repair.

Manned operations controlled onsite at Mars could obviate a need for the higher-level automated task control. While crews are present onsite, operations control might best be located in Mars orbit. The question of how to establish mission control in Mars space is

one requiring study. However, the systems cost of keeping crew at Mars is roughly an order of magnitude higher than that of keeping crew on the Moon. While a Mars base could be built up, checked out, and operated intermittently using onsite supervisory and teleoperated control, introducing greater machine autonomy can result in a faster buildup, more capable facilities, and the most productive use of precious crew time on the planet. In any case, an evolutionary program which uses the Moon as a testbed for Mars will inevitably develop machine control technologies (for reasons of efficiency) that will in turn make extensive robotic Mars operations feasible. Currently, the first human missions to Mars are envisioned to begin no earlier than 2010; even assuming that those first missions fly with then-10-yr-old technology, that allows 10 yr from now for demonstrations of consolidated and implemented automated task control capabilities. Even one year in the dynamic field of ATC is a long ime.

Robotic activity at Mars in excess of what onsite crews could enable will require advanced unmanned repair abilities. Robotic R & R will function as on the Moon, but versatile subcomponent repair without the hands and minds of onsite crew will be difficult, if not practically impossible, in the early decades of the 21st century. One might envision a dextrous, robotic work center which could, under supervisory control from Earth, dismantle, inspect, and effect repairs on subcomponents to return them for service. A more conservative approach would be reliance on yet greater component reliability, combined with extensive (mass-doubling?) inventories of spares, and awaiting crew presence. Predictable failure rates indicate, however, that **keeping a productive Mars base going without either a robotic "slave workshop" or frequent crew attention would not be feasible.**

CONTAMINATION - The oxidative chemistry of some martian soils is reactive enough to have generated conflicting results in the three complementary Viking experiments designed to detect life. One outcome is that the question of present or past life on Mars remains unresolved. Another outcome has been the suggestion that components exposed to martian soil would suffer destructive chemical attack, and that even small amounts of martian soils might be pecpliarly toxic to humans. The latter, physiological concern is outside the scope of this study, but there is as yet no known technical basis for alarm, and we would anticipate that dust-control measures developed and tested on the Moon could be designed in any case to reduce crew-system contamination to safe levels. The former, reliability concern has recently taken on the complexion of a "non-problem" at ISRU

workshops. First, design for challenging chemical environments is not new, and Earth's atmosphere is more strongly oxidative than martian soil. Second, the polymeric materials suspected of being vulnerable would be used very sparingly anyway in systems which needed to survive the thermal, vacuum and radiation environments in transit and in surface use. Finally, both Viking landers survived and performed quite well for over an entire Mars year (more than two Earth years), with no maintenance at all.

A more challenging problem for long-term systems is likely to be protection against the physical effects of windblown dust. Since the Mars atmosphere is tenuous, even its extremely high wind speeds (100 m/s) are equivalent to only moderate winds on Earth. However, particles lofted by those high-speed winds obviously contain the same kinetic energy they would at the same speed on Earth. The consequent erosive capacity of this dust and sand is great, and systems like radiators, windows, sensors and delicate equipment will suffer degradation if unprotected. Furthermore, our simple lunar approach of keeping non-hardened, less robust equipment high up off the ground would be insufficient on Mars. The same μm-sized dust particles which characterize the global dust storms will have access to equipment at all heights. At times, circumstances would appear to be like those experienced in the 1930s "dust bowl", with fine dust penetrating every unsealed opening. **More advanced provision for dust exclusion, resistance and cleaning will be required** to keep martian equipment functioning properly.

5. RECOMMENDATIONS

5.1 LUNAR BASE REFERENCE CONCEPT RECOMMENDATIONS

When the iterative design and analysis cycle is interrupted, some desirable refinements always remain outstanding. This section presents _post facto_ improvements in the reference scenario proposed by the various study participants.

1) **Increase the ratio of crew-to-cargo flights.** Tasked with maximizing the use of A & R for lunar operations, we minimized the amount of direct crew participation in the buildup scenario. The ratio of crew-to-cargo flights which resulted (2/13) was intended primarily to establish one end of the spectrum, to make a point: many of the tasks involved in establishing a lunar base could, or must, be done by machines; and controlling those machines is a practical and flexible undertaking.

An earlier crew flight, perhaps flight #2 or #3, would provide more robust prospects for assuring that the robotic activities can proceed as planned. With the capability to abort on short notice to their shielded transfer spacecraft in orbit, or rapidly configure a temporary shelter, the crew would not require a shielded surface habitat for an early visit. Another possibility is to have human crews in LLO during the first few cargo intervals. However, their supervisory role would be complicated by communications between their orbiting spacecraft and the base, and the program cost would not be reduced substantially, if at all. To provide any help not already possible from Earth, they would have to have the capability to land --- they might as well be at the base.

In a real lunar base program, sensitive to public opinion, we would expect that human crews would be sent at least once a year during buildup, despite our conclusion that the technical payoff (with regard to rapid emplacement) of that much onsite crew involvement might be low. One crew flight per year roughly doubles the number of crew flights we propose as strictly necessary, with a commensurate increase in early program cost. However, current plans call for a number of crew flights equal to cargo flights,

which our analysis indicates is unwarranted if the primary goal of the early program is base buildup.

2)   **Extend the nominal crew visit staytime to about 45 d   (1.5 cycles).** Arriving early in the lunar morning, the crew would then have: a full lunar day to perform inspections and observations; a full lunar night to perform IVA repairs, and plan process adjustments based on their observations and repairs; and another lunar day to implement the process refinements, observe the results, and monitor the performance of repaired components. The lander and habitat system, both currently sized to deliver and sustain crews of up to 8 for up to 30 d, could easily accommodate smaller crews for longer times, so a 1.5 cycle sortie staytime is well within the constraints of the reference scenario.

3)   **Send the central communications utility early**, rather than on flight #6. Otherwise, the robotic vehicles will each need to have equipment capable of supporting high-rate communication with Earth, in just the period when effective communication is most critical: the experimental, beginning stage. As with the initial PV power unit, the main transmitters can be temporarily deployed, allowing the robots to use only local transmissions right from the start. Once the habitat system is constructed, the transmitters can be relocated more permanently.

4)   **Give the precursor rovers more capability.** For the unmanned survey phase, other prospecting equipment may prove useful, like a small coring drill. The more instrumentation burdening the vehicle, and the faster results are expected, the more communciation capacity and power will be required. A high-gain antenna may be necessary. Once the rovers are converted to crew use, small utility trailers would be advantageous. A pair of manipulators has more than double the usefulness of just one.

5)   **Send a third straddler, and perhaps a third truck, or stretch out the buildup schedule.** Maintenance activity will figure so prominently in lunar base operations, particularly at the beginning (when the slope of the reliability bathtub curve is still steep and systems are being shaken down), that the contingency time designed into the vehicles' schedules may be insufficient. Since the schedules feature much downtime later on, an acceptable way to relieve the congestion may be to stretch the schedule out by just a few intervals.

6)   **Design in more detail the crew accommodations for inspection and maintenance access.** Handrails and platforms, although a mass penalty, constitute another (backup), and at times quicker and simpler, alternative to the "cherry picker" method of crew placement using the trucks. Standardized, portable eleoperation stations would allow EVA crew to control equipment wherever it was around the base.

7)   **Plan activities for the short crew visits,** and show them on the same schedule diagrams as the equipment activities.

8)   **Close-proximity and man-aboard teleoperation should be considered for several assembly and maintenance tasks;** the operator would be situated in a conditioned IVA cab directly adjacent to the manipulator(s). In this operational mode, the machine becomes a direct extension of the operator's own limbs and senses, and the loss of sensory information and performance often experienced during remote teleoperation are virtually eliminated. The result is analogous to an Earth-based backhoe operator. With respect to the robotic equipment proposed in this study, close-proximity teleoperation could be applied to the high-reach truck (by placing an operator station at the boom tip), and even the straddler manipulators.

9)   **Amend the siting constraints to preserve an open corridor directly in line with each lander approach trajectory.** Study team members with flight experience suggested that risks to the base equipment could be substantially reduced simply by leaving a street-width opening in the site plan due west of each landing pad developed.

10)   **Allow flexible ETO launch rates.** This would accommodate more efficiently the surface operations schedules deriving from constraints peculiar to base buildup. Wider launch centers at the beginning would allow more robot contingency time during the flurry of excavation required to get things started. Closer spacing later would keep the base from having to wait for shipments, and presumably would be possible with increasing experience.

Several specific trade studies were suggested during the course of our work, concerning the **lander** (capacity, optimal landing gear configuration, tipover stability, mechanisms for leg deployment, straddler access); **straddler** (size, tipover stability, contact polygon, workpiece envelope, operational redundancy); **power supply** (extended

solar field, SPS power beamed from LLO or L1, base-wide nuclear or distributed RTGs); **oxygen plant** (other designs than the tricky fluid-bed approach, and other oxygen-generating chemistries); **habitat system** (configuration, inflatable adjuncts, shielding techniques); **crew systems** (burdening the rovers, instead of the EMUs, with heavy ECLSS equipment for long EVAs); and **growth options** (other ISRU processes, alternative future "charters" for the base).

5.2   SYSTEM DESIGN RECOMMENDATIONS

Both this study and the Orbital Assembly Study, generated several specific recommendations for designing systems amenable to robotic operations on the Moon, which we list concisely here:

1)   **Factor in remote robotic and crew operational considerations (both limitations and advantages) when making every design decision, from the start.** Adapt all assembly steps, fasteners and part identification for robotic use. Make a way for everything to be serviceable. Design all systems as though everything in them will fail or require maintenance, since eventually it will. Design-for-maintenance tends to trivialize the simpler case of initial assembly. Make the robots as easy to maintain as the other base equipment.

2)   **Use a consistent, object-oriented model** for design of components, simulation of base construction activities, and derivation of robot control. Incorporate the designs directly into an object-based domain model for use in operations simulation, and actual robotic execution.

3)   **Minimize the in situ effort required.** It has been said that the way to make A & R work is to "design it out" as much as possible --- that is, take special care to keep the tasks simple. Robots work best in environments they "understand", with no surprises, and no interference. Minimize opportunities for onsite confusion. Make full use of ground fabrication, testing, monitoring and control. As expensive as these efforts may be, they will always be less than the expense of compensation during the mission. Efficient

operations at the base will be supported by massive engineering analysis on Earth. Simplicity at the base ("in flight") will greatly enhance crew performance as well. Make base elements robot-proofed, and crew-proofed as much as possible, against unintended operations.

4) **Design self-contained subsystems**, with small numbers of large sub-assemblies; make interfaces as clean as possible; maximize commonality of components, fittings, fasteners, interfaces, and protocols. Use compatible and consistent gripping interfaces for suited crew and robot effectors. Keep special, single-purpose tools to a minimum; extract maximum utility and diversity from a few devices. Insure explicit marking and coding of all objects (identification, orientation, and position). Incorporate handshaking, self-test sensing into all components, interfaces, and systems, to enable the automatic and immediate verification of proper assembly, part function and integrated system function. Configure all systems and structures to facilitate expansion by robotic equipment. Test all interfaces for "fit and function" on Earth prior to launch.

5) **Provide non-cascading access/changeout paths**. Organize the site with sufficient spacing between elements to accommodate approach to all facilities by any robot. Leave sufficient room for robotic manipulators and their sensors to get to components; preserve straight-line, horizontal access paths which avoid the need to make extraneous disconnections when removing components; use single-motion, re-usable captive fasteners. These R & R guidelines will facilitate both robotic and EVA crew operation.

6) **Assure means for human activation of all tasks**. This has two parts: avoid task designs which EVA crews (directly with proper hand tools, or by teleoperating machines) could not accomplish; and make nominal robotic operations "crew friendly". Robotic and crew procedures should follow the same logic flow, and the boundary between supervision and teleoperation should be soft and transparent. Provide status displays so the crew can understand where the robots are and what steps are next. Maintain system "visibility" to aid in crew trouble-shooting, streamline task supervision, and ease teleoperated takeover when necessary. Include safing systems that defer to crew who are present at the worksite, to prevent accidents.

7) **Exploit indigenous features.** Use suspension of parts from cables to achieve vertical alignment. Design components for deployment or assembly while suspended,

before anchoring to foundations. Make use of local materials for anchoring, foundations and shielding.

8)   **Design components to be recycled** when defunct. Parts that can be re-used will be. And all processed materials on the Moon are exceedingly valuable; reworking high-grade materials into other uses can await that capability, if discarded items are stockpiled retrievably.

5.3   TECHNOLOGY DEVELOPMENT RECOMMENDATIONS

We believe that no new fundamental science breakthroughs are required to permit extensive A & R for lunar operations. That is, nothing we have envisioned depends on discovering something new. However, much work needs to be done to collect existing and emergent technologies, adapt available solutions for use in space and on the Moon, develop real prototype equipment, and qualify it for use in building a manned base. The technology is not ready to operate a lunar base now, but the state-of-the-art is positioned well to bring the technology to readiness by 2000. Several specific areas deserve directed effort.

Available planning, modeling, and scheduling tools for construction are insufficiently detailed to drive robotic, or even human-executed, operations in the lunar environment. Models, execution plans, and schedules must be expanded into well defined, discrete, executable actions for robot or human. Currently models and plans for Earth-based construction emphasize the finished product, a pristine or determinate site, and the parts from which to construct, but do not include detailed incremental descriptions of the state of construction such as is necessary to determine the next action. The level of detail and expected complexity of lunar basing operations is potentially overwhelming for current methods. Given a sufficiently detailed base concept, models and execution plans could be automatically generated at the finest grain of detail, from libraries of primitive operations, procedures, and generalized/parameterized component models.

Further investigation is required into mining operations, specifically techniques for the gathering and loading of regolith materials. Little experience exists from terrestrial

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mining analogs that is directly applicable to the unique lunar combination: shallow plowing of sand-like material with solid inclusions; loading granular rubble; low gravity; and particularly limited power availability. Appropriately modeling, simulating, or mocking up the characteristics, behavior, and associated contingencies of regolith-mining is a significant but necessary task.

Simulation of lunar assembly, construction and maintenance operations (including representations of the site, robot, and task) are needed to facilitate verification and/or further development of appropriate modeling and planning. However, simulation is not sufficient to substantiate actual capabilities and completely reveal shortcomings; implementation of prototype autonomous robotic construction systems is necessary.

The viability and feasibility of the proposed robotic systems need to be further investigated in light of actual power requirements and ensuing machine weight. Actualized robots typically differ vastly from first concepts, as detailing and unseen considerations arise. Most surprises will be adverse, and commonly occur as escalations of power, weight, computing, telemetry, and control requirements. No proven systems or development experience exists specifically for modern lunar surface robotics. Although Earth-based analogs are an appropriate basis for initial concepts as developed in this study, they are not so specific or detailed as to be the sole basis of critical power and weight evaluations for the lunar application.

System-wide features which yield more robust, reliable, fieldworthy robots are required for the lunar setting. No precedent of a work robot exists with complete qualifications for the lunar basing constraints of: temperature extremes and fluctuations, abrasive dust, low power with ambitious work capabilities, light structure, EM fault tolerance, and long-term radiation resistance. Specific technologies requiring development to support equipment development include: high-force, large-travel actuators that can withstand the lunar environment (particularly temperatures and abrasives); long-lived, all-metal wheels for mobile robots; and robust, low-power range scanners. Components and systems should be generally designed for modularity, functional redundancy, and simple change-out.

The feasibility to achieve a wider range of manipulation capabilities should be investigated. Currently available manipulators are specific to a narrow range of accuracy, strength and reach, and those able to handle larger payloads and reaches can do so only

with gross accuracy. Control methodologies, algorithms and mechanisms should be further developed or investigated, to determine if fewer numbers of more capable manipulators can be developed to perform diverse tasks for lunar basing operations. Such versatile commonality can introduce important program cost benefits.

High-strength, light-weight materials with special-property inserts need to be incorporated into the robotic equipment design to minimize weight. These material considerations must be made early on in the development of this equipment, as the shape, configuration and capabilities of the equipment will be significantly affected.

Sensors and processing specific to automated manipulation and machine vision require further development and synergy to achieve execution of primitive subtasks and procedures at the physical level. This includes non-saturating CCD eyes that can handle the harsh lighting contrasts found on the sunlit lunar surface. Robust auto-vision algorithms and miniaturized, high-capacity image processors will be required to support A & R lunar operations as discussed in this study. High-resolution ground-penetrating survey techniques for anhydrous, metal-containing media are enabling for adequate site surveying.

Intrinsic safeguards need to be incorporated into the robotic systems, including: sensors and associated processing; interlock logic; crew awareness; innate tip-over protection; health monitoring; and environmental management for lunar conditions. Embedding and managing sufficiently-detailed diagnostics to enable the type of lunar operations we propose is a notable challenge.

Teleoperation is viewed in this study as a backup mode of execution for many activities, but is viable as a primary mode and should be more thoroughly developed. Prototyping is necessary, and if done in conjunction with both prototyping of autonomous systems and prospective training of crews, synergy is possible which might mix, calibrate, and optimize the most appropriate scheme.

Automatic rendezvous and docking systems need to be qualified before unmanned cargo transfers can be accomplished in LLO. Obstacle-avoidance systems must be developed using lunar-environment simulations to support automated cargo landings.

Better crew systems are required to support extensive onsite activity. Specifically, non-tiring EMU gloves continue to be elusive, and suit weight in lunar gravity is a potential

problem. Tethered ECLSS means need to be investigated and traded, so that vehicles might be burdened by such long-duration equipment instead of the crew themselves.

Devices and methods need to be developed for site infrastructure to support robotic operations. Specific areas of development include: positioning beacons to assist in navigation; telemetry, data processing, and operator stations for multiple and coordinated robots, and supplying onsite crews with predictive task information; management methods for worksites featuring robots and crew side-by-side; and facilities for fleet repair, maintenance, powering, and storage. To facilitate more continuous Earth-based teleoperation of lunar robots in a variety of settings, telemetry needs to be investigated and developed for Farside operations.

Several important follow-on study tasks we recommend are:

1)   A site-preparation engineering geology study for the Moon and for Mars, to set standards for equipment design.

2)   A detailed study of robotic Mars surface operations, to scope the problem.

3)   A comparative system-design study of alternative ISRU processes for both planets, to determine those most worthy of detailed effort.

4)   A detailed reliability analysis of a well-definable element such as a rover, the results of which could be used to calibrate the first-cut results for other elements.

5)   A study of human performance in the reduced-gravity and harsh-lighting conditions encountered on planetary surfaces.

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6. CONCLUSIONS

The assembly, emplacement, checkout, operation and maintenance of equipment on planetary surfaces are all part of expanding human presence out into the solar system. They should be treated with importance equal to any other aspect of exploration missions. Without tenable solutions for all these tasks, planetary bases cannot come to pass. Without an integrated, unified solution for all of them, we cannot afford even to try.

Even more clearly on planetary surfaces than in orbit, there is no such dichotomy as man *vs.* machine. Neither can fulfill our potential for exploration, discovery, and achievement without the other. Expanding human presence offworld is an essential part of this nation's National Space Policy. The infrastructure required to sustain and promote human life and work in these places is complex, heavy and extensive. Machines are needed to build, run and sustain the infrastructure. And finally, methods for controlling the machines, managing the work, and handling the unexpected are required. Ultimately, this loop closes again with the human. Projections of space futures cannot approximate reality unless they take full prospective advantage of the innate capacities of humans and machines together.

In this study, we have presented a single-point design, a reference scenario, for lunar base operations. It focuses on an initial base, barely more than an outpost, which starts from nothing but then quickly grows to sustain people and produce rocket propellant. The study blended three efforts: conceptual design of all required surface systems; assessments of contemporary developments in robotics; and quantitative analyses of machine and human tasks, delivery and work schedules, and equipment reliability. What emerged was a new, integrated understanding of how to make a lunar base happen. Details will change with further work, but the principles uncovered --- the priorities, the technologies, the pitfalls, the potential --- will remain.

The overall goal of the concept we developed has been to maximize return, while minimizing cost and risk. We presumed no scientific breakthroughs. We baselined technology which we already have, already understand, or already are developing for other applications. However, we assumed that the unprecedented undertaking of establishing a planetary base could motivate adapting a wide variety of innovative work to the arena of

space operations, and drew from that work accordingly. We identified the most promising directions for immediate engineering effort, which can realize feasible lunar operations at the earliest possible time.

Our operations concept stresses those aspects of lunar operations least understood so far: machine capability, surface system equipment design, day-to-day work schedules, and reliability. The concept exploits machines wherever and whenever they may be appropriate, with the goal of reserving valuable crew time for supervision, dextrous repair, long-range planning, adjustment, experimentation, and discovery. The minds and hands of the crew are thus complemented by the strength, reach, consistency, untiring operation and relative immunity to the EVA environment of machines. With that combination, the base can run smoothly, produce efficiently, and expand quickly, while our human understanding grows and our foothold in space firms.

Our base concept uses solar power. Its primary industry is the production of liquid oxygen for propellant, which it extracts from native lunar regolith. Production supports four lander flights per year, and shuts down during the lunar nighttime while maintenance is performed. Robots replace malfunctioning components with spares, and bring faulty units to a pressurized workshop. The base supports and shelters small crews for man-tended visits, during which the crew repairs the backlog of defective components, oversees operations and performs experiments. A simple set of three vehicle types performs all mobile operations, including site surveying, lander offloading, mining, beneficiation, excavation, paving, construction and assembly, surface transportation, waste deposition, maintenance, and scientific exploration. Resource mining and site preparation are two ends of the same process. Machines use automated task control, supervised by human crews in space and on Earth, and backed up by extensive Earth-based engineering support and the alternative of teleoperation. The base integrates almost 400 t of equipment (including spares) brought from Earth, together with native lunar materials, to transform a virgin lunar site into an efficient research and production facility, in just four years. What makes such a concept tenable is the methodical incorporation, from the very beginning, of realistic abilities and constraints, and rigorous quantitative consistency throughout the scenario.

This study can serve as a point of departure for more extensive, and more detailed, engineering analyses of the planetary base problem. Much more work in integrated planning, technical design, reliability assessments and detailed scheduling is required. However, what is most urgently needed is for work to proceed on the enabling A & R

technologies specifically outlined in this report, as they are largely invariant. Program priorities and national commitment, not limits on our technical ability, will define the way we eventually establish the first lunar base. Our work signals a departure from approaches which develop surface system requirements and then match equipment concepts to them directly. Instead we strove for extracting a lot of versatility out of an intentionally limited set of equipment, acknowledging the present trend toward nearer-term, less grandiose, more incremental ways of exploring space. The most exciting conceptual prospects on the horizon push this trend yet further, stripping away even more of what is ultimately desirable, from what is immediately affordable and acceptable. When these new efforts converge, what will have survived will be the irreducible and economical seed of a real base buildup plan. No matter where it leads, after all, our return to the Moon will begin with one flight.

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