



Lunar Surface Systems Supportability Technology Development Roadmap

Final Report

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Executive Summary

Most of this report was written in 2009. Since then, many program changes have been made to the dates and missions discussed herein. However, NASA remains determined to explore our solar system and to having humans in space. The principles of supportability discussed in this report remain critical to the success of human exploration missions to low Earth orbit and destinations beyond.

This roadmap is intended to serve as a guide to developing technologies specifically to meet the needs of the Supportability Project of Constellation Lunar Surface Systems (LSS) and may be applied to other segments of the program. The effort was jointly funded by the Constellation Supportability, Operability, and Affordability Office and the Supportability Technology Project under the Exploration Technology

Development Program (ETDP). The initial study focused on maintenance and repair (M&R) technologies to be used by LSS. However, it became clear that the lessons learned from the various contributors indicated that the study needed to deal with a wider context of lunar logistics. The study team involved five NASA centers: the NASA Johnson Space Center, the NASA Kennedy Space Flight Center, the NASA Glenn Research Center, the NASA Langley Research Center, and the Jet Propulsion Laboratory. The study was also supported by the U.S. Navy's Naval Air Systems Command (NAVAIR) and Naval Sea Systems Command (NAVSEA) and incorporated prior work of the U.S. Air Force Research Laboratory (AFRL). General M&R practices and lessons learned were provided by the NASA Shuttle Logistics Depot, the NASA Spacecraft Services Depot, and the International Space Station (ISS) Office of Space Operations.

The study considered the experience of in situ M&R by both the U.S. and Russian space programs, which differ in maintenance philosophy. Their philosophies are driven by the underlying logistics capacity available and the value placed on resources. For example, the U.S. program places high value on crew time, whereas the Russian program places a high value on the flight hardware. On the ISS, the United States exploits the space shuttle's large payload and return capability to minimize crew maintenance time; therefore, flight hardware was designed as quick-to-replace, modular orbital replacement units (ORUs). In contrast, the Russian program employs a less costly but limited logistics payload capacity (with no return capacity) that requires more crew time and investment in training for in situ maintenance. For lunar missions, a cargo vehicle's payload fraction is expected to be one-fifth that of an equivalent vehicle going to the ISS. Furthermore, flights may be much less frequent (only two per year) with no capacity for returning hardware. With such constraints, the logistics and maintenance strategy will likely be more like the Russian strategy. The study team considered what capabilities are needed for a hypothetical lunar maintenance depot and determined that significant in situ repair capability dramatically increases the demand for crew time, training, and equipment. A primary need is for capabilities that minimize the operational impact on the crew.

Specific high-level needs were derived from the LSS Surface Architecture Reference Document (SARD). Lower level needs were identified by ongoing Supportability Project tasks and prior studies of ISS by the earlier Component-Level Electronic-Assembly Repair (CLEAR) task. CLEAR established that roughly half of ISS on-orbit problems were in electrical systems. Examination of the ISS on-orbit problem reports indicated that as high as 63 percent could have benefited from in situ diagnostics and that 42 percent would have been resolved by a component-level repair. An alarming number of on-orbit problems had a root cause recorded as "unknown." For successful in situ maintenance, there is a clear need for greater depth of diagnostics and prognostics to isolate the problems down to the lowest replaceable component.

A supportability philosophy and architecture for M&R for lunar and Mars missions was developed by the LSS Supportability Project representative. In addition to defining the overall processes, this section describes a path toward achieving operations with near zero logistics. This supportability approach is outlined in an appendix to the LSS SARD. For program sustainability, minimizing lunar resupply logistics and related launch costs can prevent the cost of lunar operations from barring future exploration. This approach was used to define an LSS supportability technology development strategy. The strategy focuses on capabilities that achieve a high degree of "logistics independence" and that minimize operational complexity.

In addition to the process technologies required for maintenance, the strategy includes embedded technologies that make the systems maintainable. The strategy also considers exploiting scavenged flight hardware and materials as an early form of in situ resource utilization. Scavenge and recycle (S&R) technologies are expected to play a key role in the ETDP supportability technology portfolio.

Technologies that can meet supportability needs often impose size, weight, and power penalties on flight hardware or require additional payload capacity. These penalties are very difficult for individual system designers to accommodate, and thus, designers will resist adopting supportability standards. Further supportability operations will also demand resources such as power, data bandwidth, and crew time and training. Conventional technologies will not be adequate to address the needs without excessive

penalties and may be ineffective in a lunar environment. New techniques will be needed to minimize the initial payload mass, minimize resource consumption, and exploit available resources including the natural lunar environment.

LSS supportability technologies are organized into embedded and process technologies, which are both composed of three categories. The three categories are diagnostics, test, and verification (DTV), M&R, and S&R. Although the central theme is M&R, the other two categories are essential in building a complete supportability infrastructure. DTV capabilities detect and isolate problems and isolate the root cause for effective repairs. DTV also verifies that repairs are effective and that hardware is safe to return to service. S&R requires many of the same technologies that M&R requires, and M&R can use hardware scavenging as a source of spare parts and repair materials. Scavenging not only reduces payload mass but makes the return on investment for maintenance technologies more effective. Consistent with the LSS supportability technology development strategy, scavenging of flight hardware also transitions the architecture toward greater resource independence.

Embedded supportability technologies include embedded devices, design features, and base material selection that make the hardware maintainable and scavengeable. Process supportability technologies involve the specific processes, instruments, tools, and consumables that are used to perform maintenance and are external to the flight hardware. Embedded and process technologies are highly interdependent. The effectiveness of a given process depends on the embedded feature of the hardware. Much of embedded technology is aimed at simplifying operations which, in turn, minimizes process hardware. This technology roadmap indicates that there are 15 capability subcategories (6 embedded and 9 process subcategories). A supportability capability may have multiple technology solutions, and specific supportability criteria are needed to ensure that the most appropriate technology is selected. For system developers that may need to embed a technology, the criteria also apply to hardware design evaluation to ensure that the end product is supportable.

Embedded and process technologies are infused by different methods, and thus the project established different selection criteria. For embedded technology, the criteria place value on hardware accessibility, embedded diagnostics and prognostics, common components and interfaces, and reconfigurable, scavengeable hardware. For process technology, the criteria consider lunar environment compatibility, process dependencies (a measure of complexity), resource effectiveness, and high process utility.

Embedded and process technologies will follow parallel paths as they are developed, but they are interdependent. For example, a process technology may also require a corresponding embedded technology to be infused into flight hardware. Embedded technologies must be infused into the flight vehicles, and thus their development path is linked to the vehicle development timeline. Four development increments were developed for this supportability roadmap. Increment 1 is almost entirely embedded technologies linked to the Altair development. The three remaining increments are process technologies that are staggered on roughly 2-year centers. Increment 2 is primarily composed of DTV and M&R technologies that could be used on early Altair sortie flights. Increment 3 is aimed at initial Lunar Outpost (Habitat 1) capabilities, where operational damage and wear are expected to require M&R capabilities. Increment 4 is aimed at outpost completion and includes significant S&R along with advanced repair and in situ fabrication capabilities. This incremental approach allows ETDP to focus resources on more immediate supportability applications while allowing low Technology Readiness Level, but high value, technologies to evolve and merge with the program at the appropriate point.

This “Lunar Surface Systems Supportability Technology Development Roadmap” is a living document that is expected to evolve. It is designed to be flexible and can be applied to a varied mix of human and robotic operations. Supportability capabilities are needed to keep operational costs low so that the program can move on to accomplish future missions. Supportability is expected to shape the operational infrastructure of human exploration.

1.0 Introduction

Most of this report was written in 2009. Since then, many program changes have been made to the dates and missions discussed herein. However, NASA remains determined to explore our solar system and to having humans in space. The principles of supportability discussed in this report remain critical to the success of human exploration missions to low Earth orbit (LEO) and destinations beyond.

NASA's Constellation Program (CxP) is involved in ongoing development of Lunar Surface Systems (LSS) architecture that could ultimately establish a Lunar Outpost capable of sustaining long-term occupation by human crews. The NASA Exploration Technology Development Program (ETDP) and the Supportability, Operability, and Affordability Office jointly funded a multidisciplinary study that examined the technology required to achieve a supportable and sustainable lunar program. Supportability, operability, and affordability are aspects of the program that are difficult to quantify in the development stage but that, ultimately, will affect the overall cost of the program once facilities are established and operational.

NASA is currently developing new vehicles with the multiple goals of reducing the human risks and cost of space flight while expanding the reach of human exploration. Launch costs are ultimately applied to the payload delivered, and this study considers technologies that extract the highest possible utility from these payloads in lunar operations. This technology roadmap identifies needs, defines capabilities, and identifies candidate technologies that will be developed. This roadmap is focused on LSS maintenance and repair (M&R) and the related logistics of supportability. This study considers lessons learned from NASA flight operations, NASA logistics depot experience, and lessons learned from military flight systems.

The initial effort was to characterize existing space-based maintenance and related ground support for the International Space Station (ISS). For the ISS, the maintenance strategy is to remove and replace (R&R) modular orbital replacement units (ORUs, Ref. 1). This approach was adopted primarily because of constraints on crew time and the need to return systems to full function and restore redundancy as quickly as possible. The approach envisioned by ISS would have been supported by a robust logistics infrastructure with resupply intervals as short as every few weeks. In contrast, NASA's planning for the Lunar Outpost currently assumes only three to four missions per year with two crewed missions and one to two cargo missions (Refs. 1 and 2). The payload delivered by an expendable cargo vehicle to the lunar surface is roughly 22 percent of the payload that the same vehicle would deliver to the ISS in LEO (Ref. 3). This puts further pressure on the program to design payloads with high utility to match the higher payload cost. Unlike the ISS, lunar hardware is not part of a closed-loop logistics transportation cycle. The ability to return hardware, repair it, and relaunch it was based on the space shuttle's massive capability to move hardware between Earth and orbit in both directions. For lunar missions, the roughly fivefold increase in payload delivery cost, the one-way transportation of hardware, and the dramatically reduced frequency of launches drives the need for a new supportability strategy.

Recently, NASA's LSS project began considering concepts for extending repair capabilities to surface operations, where crew members and robotics could perform repairs and routine maintenance. This could involve removing line replaceable units¹ (LRUs), deintegrating assemblies, diagnosing and repairing at the subassembly and component level, functional test and reintegration steps, and finally returning the hardware to service. This represents an unprecedented level of complexity and potential risk if improperly executed. However, it also represents an unprecedented capability and flexibility that empowers the crew to act effectively in response to problems. This would be a major paradigm shift for NASA space missions and must be carefully considered in the lunar architecture.

Many of supportability technologies needed to enable this level of maintenance will be embedded in the actual flight hardware to ensure that hardware is accessible, serviceable, and even scavengeable. Therefore, the technology must be defined early and infused into the spacecraft design. Many supportability technologies represent new process technologies that can operate in an extremely resource-scarce environment where conventional technologies cannot operate. Like the ISS, the Lunar Outpost will be required to minimize the demand for crew time and crew training. Therefore, this roadmap also considers

¹The line replaceable unit (LRU) and orbital replacement unit (ORU) are equivalent assemblies.

the operational context and the need for ground support of the crew to ensure that maintenance operations are effective and safe and do not pose risks to the crew or systems.

Additional information is provided in the appendixes. Appendix A calculates the relative payload mass fraction, Appendix B describes the tools and equipment for ISS flight operations, Appendix C describes the hands-on repair process for the NASA Shuttle Logistics Depot (NSLD) Avionics Laboratory, Appendix D discusses supportability beyond Earth orbit, Appendix E illustrates an LSS repair scenario, and Appendix F defines the acronyms used in this report.

2.0 On-Orbit Supportability Strategies and Lessons Learned

This section examines some past and current practices for supporting the logistics and repair needs of space-flight missions. The discussion begins with a look at previous missions, including Apollo, Skylab, and Mir. It then focuses on current practices and lessons learned from the space shuttle and the ISS. Department of Defense contributors have provided additional insight to maintainability that is based on military experience and lessons learned.

2.1 Apollo Era On-Orbit Maintenance

The experiences of the Apollo, Skylab, and Mir missions point out the occurrence of and recovery from faults and failures. Because of the short mission durations, the primary strategy for major failures during an Apollo mission was to abort the mission and return to Earth. The events of the Apollo 13 mission illustrate this plan. Other Apollo missions experienced far less critical faults and failures, including a damaged television camera, a failed potable water tank valve, and damage to a lunar rover fender. In these cases, the crew used redundant systems operated at a reduced capacity or, in the case of the damaged fender, scavenged from materials on hand to repair the damage (in this case, using lunar surface maps clipped in place as a replacement fender). Determining the fault in the case of the television camera and valve required postflight inspection and testing of identical equipment to determine the root cause of the failures. The later Skylab missions suffered from damage incurred during the initial launch, reducing the vehicle's capacity to manage heat and generate power. The first two crews performed repairs that allowed Skylab to operate and demonstrated the capability of crews to perform repairs and recover from potentially major faults or failures.

2.2 Russian Mir Strategy

For the Mir station, the Russian Space Agency planned for a high degree of crew involvement in repairing and maintaining the vehicle's systems. The general maintenance philosophy used by the Russians on Mir is still in use on the Russian segment of the ISS. The philosophy has been characterized by the phrase, "Run it until it breaks" (Ref. 4). This should not be interpreted as lack of *preventative maintenance*, but rather that hardware is operated until it reaches its end of life (EOL) without *preemptive maintenance*. Cosmonauts replace faulty hardware if a replacement is available, or they find a way to diagnose and repair the system or to operate with a degraded system until a replacement can be provided. In lieu of a spare and depending on the donor system's criticality, the crew is permitted to cannibalize hardware from other systems at the expense of redundancy. Replacements might be manifested on the next available flight, but there is an emphasis on repairing the system at hand. The crew work load increased as Mir continued operations well past its expected lifetime. From March 11, 1995, to May 31, 1998, cosmonauts performed 137 maintenance activities, some major, and all were successful in replacing the part or repairing or working around a fault (Ref. 4).

Unlike the American approach, the Russian approach does not appear to depend heavily on logistics and modular ORUs. The Russian approach emphasizes the crew's roles and responsibility for spacecraft maintenance. It depends less on sophisticated technologies and depends more on the diagnostic and repair skills of the crew. In the Russian approach, the crew has much more latitude in determining a course of

action and has demonstrated resourcefulness in the diagnosis and repair of problems. The approach is more consistent with a resource-scarce environment, where the installed hardware has an intrinsically high value and is worth the effort to repair in situ. In contrast, with the American approach, crew time is highly valued and focused on mission objectives, and faulty hardware is expendable. There is no right answer; instead, there is a tradeoff based on the expected availability of spares and of crew time for maintenance.

2.3 International Space Station On-Orbit Maintenance Philosophy

The ISS philosophy is to use available resources to maintain, repair, and replace failed ISS hardware components and return the affected systems to their original configuration and efficiency. NASA's baseline approach for the ISS is to R&R defective ORUs in their entirety. This approach is based on the idea that replacing ORUs requires less crew training and reduces the amount of crew time required to make repairs, thus increasing the amount of time for performing science activities. In limited cases, where time considerations and the lack of a spare ORU do not permit replacement, repairs are made to a part of an ORU. This repair philosophy also requires cooperation from the international partners. This includes the planning, training, and execution of repair procedures and providing repair kits with unique tools and parts. The sharing of tools between partners is expected, and all affected partners must agree on a plan that calls for scavenging from one system to restore functionality to another.

Eleven years of operation have provided insights into supportability operations and lessons that can be applied to the next generation of vehicles and missions. NASA should include maintenance and reliability requirements in contracts for building parts, systems, and vehicles; should define an integrated logistics support (ILS) process; and should develop a maintenance and operations concept early in the design phase. An ILS manager should have a senior position in a project, and logisticians should be assigned to design teams as a resource (not as designers) for reparability and maintenance concepts. Designs should stress the commonality of parts, components, and fasteners to the greatest degree possible and should decide on a single system of measure (i.e., metric or English). Design should be done with reparability and robustness of the finished parts and systems in mind. Missions should also be provided with a comprehensive set of tools to allow for M&R and to provide tools for testing system or part performance, for diagnosing faults, and for verifying a repair before returning a part or system to service.

2.4 Recommendations for Tools and Equipment From International Space Station Flight Operations

The following recommendations for tools and equipment came from lessons learned during flight operations on the ISS:

- Enforce common fasteners and tool sets
- Eliminate recurring calibration cycles and integrated calibration features
- Use common intravehicular and extravehicular activity (IVA and EVA) tools
- Minimize the impact of an additional component-level tools set
- Go 100-percent metric
- Provide durable, portable tool storage and caddies with improved user friendliness
- Ensure that logistics accounts for the consumption of tool bits, blades, dies, and extraction tools due to breakage (and extraction tools)
- Provide a wide range of portable visual magnification
- Avoid the need for process containment that reduces user access and visibility
- Reduce or eliminate the need for certification after repairs

2.5 Programmatic Recommendations From International Space Station Flight Operations

The following programmatic recommendations came from lessons learned during flight operations experience on the ISS:

- Provide ILS education to subcontractors and contractors as well as civil servants
- Make logistics and supportability a designer responsibility
- Track logistics requirements and review them at project design milestones
- Establish a maintenance operations concept early in the development program
- Enforce explicit availability and maintainability requirements (use “shall”)
- Anticipate obsolescence and the loss of key vendors; acquire plenty of spare components early
- Build an in-house component-level capability and skills for the long term
- Maximize opportunities to add robustness (life margin) to minimize life-cycle costs
- Provide incentives for supportability that match the incentives for size, weight, and power constraints
- Centralize design and operations information with comprehensive search capability

2.6 Lessons Learned From the Department of Defense

The experiences of the U.S. Navy’s Naval Air Systems Command (NAVAIR) with military aircraft contribute lessons learned and concepts to use in future vehicle development and operation. One important concept is the testability of a system. Designers must provide a built-in test (BIT) that includes fault isolation to the component level to provide faster diagnosis and insight into the root cause of a fault.

In addition, designers must provide tools and processes to test the operation of a system, must isolate faults, and must perform postrepair tests to determine the success of the repair. The design for testability must take a balanced approach between BIT and external capabilities. BITs are useless when the electronics are rendered inoperable because of a power or communications outage. External equipment is still needed to pick up where BIT capabilities fail. Therefore, testability still requires external equipment, tools, and corresponding crew training.

The NAVAIR experience also includes managing contracts and relationships with outside contractors or vendors. Contracts must be written to incorporate new technologies and testability functions. The maturity of technology, as well as lack of incentive, can lead a prime contractor to forego integrating in testability. The testability and supportability concepts should also be encouraged as a cost-saving measure for the contractors. Incentives should positively affect contractor balance sheets as well as improve the supportability of the end product for the end user by reducing testing and maintenance costs.

3.0 Lunar Capability Considerations From International Space Station Operations and NASA Depot Experience

The following sections summarize the considerations for and issues of extending Earth-based depot capabilities to a notional lunar depot. These considerations and recommendations were provided by NASA logistics depots currently supporting the space shuttle and the ISS. Because of the constraints on crew size and logistics, some extraordinary and innovative techniques may be needed to allow Earth-based depots to support a lunar depot.

3.1 Crew Operations and Equipment Considerations

3.1.1 Interactive Multimedia for Crew Skills Consideration

Crew training, Earth technical support, and interactive multimedia (including interactive three-dimensional visualizations of assemblies, drawings, and processes) are needed to provide in situ familiarization and to refresh crew knowledge and skills before repairs are performed. The crew must

have acquired skills to handle maintenance at multiple levels (LRU, shop replaceable unit (SRU), and component level) including disassembly and reassembly, diagnostics, and repair. Repair skills are required for isolating various component-level faults, including removal and replacement. Furthermore, crews must be provided with multimedia training in the operation and maintenance of test equipment at the LRU and SRU levels. The multimedia approach will allow the crew to practice or virtually rehearse complex tasks prior to putting any equipment at risk.

3.1.2 Equipment Calibration Consideration

The lunar depot must consider equipment and tool calibration capability to ensure that all measurements remain true and within their specified tolerances. On Earth, calibration is governed by the science of metrology and is performed hierarchically by calibration and standards laboratories throughout the United States and the world. In a constrained lunar environment, self-sustained metrology processes (calibrations) must be incorporated in the design of equipment and measurements as much as possible to minimize or eliminate the transportation of equipment back and forth to Earth. Fundamental and primary standard calibrations now performed at primary standards laboratories, along with innovative techniques in traceability, may have to be performed in the lunar environment to accomplish calibration objectives.

3.1.3 Repair Process Materials Consideration

Repair processes often require chemicals with special containment requirements and limited shelf life. Lunar depot operations must develop innovative materials and processes that simplify storage and containment requirements.

3.1.4 Problem, Corrective Action, and Configuration Management

A lunar depot will need an automated means of managing the overall process of responding to problems, preparing procedures, recording and maintaining quality control records, and tracking the configuration of individual items. This includes the postrepair (as-repaired) configuration, and it requires synchronizing information between the lunar depot and Earth-based logistics support centers.

3.1.5 Root-Cause Analysis Consideration

Supportability will need the capability to perform materials and process evaluations and failure analysis for root-cause determination of hardware failure. The capability is needed to deal with the lack of a practical way of returning faulty hardware for ground-based analysis. Over time, root-cause evaluations will become increasingly important in understanding and preventing recurrences.

3.2 Flight Hardware Design Considerations

3.2.1 Hardware and Equipment Commonality Consideration

Past projects considered commonality primarily from a program life-cycle cost perspective. For LSS, however, commonality is required to make in situ component-level M&R viable. It is also essential if scavenging of spares from spent flight hardware is used as a logistics strategy. Electronics module commonality allows a midlevel electronics design to be used in multiple applications (e.g., the pyrotechnic initiator controller) and to be supported by a common set of diagnostic and repair tools. Electronic component and specification commonality reduces the number of component spares and allows components to be scavenged. Connector and harness commonality can minimize the quantity and variety of special tools, contacts, and spare parts. Mechanical fastener and hardware commonality not only reduces tools and spares, but simplifies assembly operations with fewer tool changes. Hardware must be designed to avoid custom, single-purpose equipment and to utilize common standard test equipment—such as oscilloscopes, meters, and analyzers—and tools, such as torque wrenches.

3.2.2 Manufacturing Materials and Process Consideration

Judicious use of materials and innovative design techniques in manufacturing will be required to facilitate M&R in the lunar environment. The manufacturing materials and the processes selected need to ensure reparability. The method of manufacturing and use of materials can restrict or prevent the repair of components. Earthbound repair processes often require materials and chemicals with special containment and limited shelf life. When materials need to be reapplied, easy-to-apply substitutes that reduce complexity and the need for process containment should be considered.

3.2.3 Embedded Capabilities Consideration

The extent of equipment needed for lunar M&R and the overall viability of in situ supportability depends on embedding diagnostics, repair, and test in the original design. Hardware needs to embed design features that ensure ease of access and simplify disassembly and reassembly. Designers can improve the feasibility of SRU or component-level repair by embedding capabilities that would minimize the external test equipment, adapters, fixtures, hookup cables, tools, and related crew training. For electronics, this includes embedding repair capability by incorporating test points, diagnostic connectors, and self-diagnostic software designed for troubleshooting to the component level.

3.2.4 Delta Acceptance Test Consideration

Flight hardware should be designed to limit the degree of revalidation and retesting (delta acceptance test) required for repairs. Where possible, design should minimize the need for a validated test set and should employ standardized repair procedures. Fault-tolerant electronics must provide fault isolation to minimize the external or subsystem damage caused by an LRU or SRU failure. This system fault-isolation capability should also be extended to protect the system and permit in-system LRU checkout of repaired hardware. This will reduce the need for dedicated external test equipment and interface emulators.

3.3 NASA Depot Mean-Time-to-Repair Data

The NSLD and the NASA Spacecraft Services Depot (NSSD) at the NASA Kennedy Space Center provided estimates for labor hours required to repair various types of on-orbit hardware. Only a portion of the ISS ORUs is processed in these facilities. The estimates were based on a mix of space shuttle and ISS hardware. The data can be used in general repairs performed over an extended period. The study looked at how hands-on repair time is portioned between four primary levels of repair. Note that ORUs and LRUs are equivalent assemblies.

- **System repair:** An ORU is replaced with a spare.
- **ORU repair:** An intermediate-level assembly, or SRU, is replaced.
- **SRU repair:** A faulty SRU is diagnosed, and faulty components are replaced.
- **Component repair:** A single component is restored or remanufactured.

Table I summarizes the hours spent on the repair of generic hardware (commonality groups). The numbers reflect the hours spent in technician hands-on processing in each level of assembly in NASA's NSLD and NSSD. Overhead is not included. Component repair time was very low, and because it was

TABLE I.—REPAIR LABOR HOURS

Level of repair	System level (ORU ^a replacement)	ORU level (SRU ^b replacement)	SRU level (component replacement)
Time, hr	49.0	258.2	244.8
Normalized repair	1.0	5.3	5.0
Remove and replace time, hr	0.19	0.20	0.23

^aOrbital replacement unit.

^bShop replaceable unit.

done infrequently at the depot level, it was omitted. System repair (ORU replacement) was the only level performed on orbit; thus, system repair times are used as a reference. ORU- and SRU-level repairs were roughly 5 times longer than system-level repairs. Therefore, ORU-level repairs would require allocating 6 times more crew time than for a system-level repair, and SRU-level repairs would require allocating 11 times more crew time.

Also shown in Table I is the portion of the time spent directly in the physical R&R activity alone without pre- and post-R&R activities. The pre-R&R activity involves setting up the equipment and hardware, disassembling it, and performing diagnostics. The post-R&R activity involves reintegrating hardware, testing and revalidating hardware integrity, dismantling the setup, and cleanup. An avionics repair end-to-end process at the NSLD facility, shown in Appendix C, illustrates the complexity of these ancillary processes. The actual replacement of the hardware as a percentage of the overall time required at each level was

- 19 percent for ORU R&R
- 20 percent for SRU R&R
- 23 percent for component R&R

With roughly 20 percent of the time at each level spent in the physical repair process, the remaining 80 percent of the time was spent performing pre- and post-R&R process tasks.

The data indicate that maintenance beyond the system level will cause a dramatic increase in crew labor, particularly if it extends to component-level replacement. The crew labor penalty diminishes the payload benefit and thus far has been a barrier to lower level repairs. A maintenance strategy that involves low-level hardware replacement must reduce crew time by eliminating or reducing tasks surrounding the actual repair:

- Increase ease of access
- Minimize diagnostics setup and execution time
- Minimize violation of hardware integrity
- Minimize deintegration and reintegration tasks
- Minimize postrepair testing

Currently, the technology program that deals directly with the full scope of access and rapid integration is the Plug-N-Play (PnP) Satellite project of the Air Force Responsive Space Technology effort.

4.0 Supportability of Missions Beyond Earth Orbit

The CxP architecture is a combination of vehicles, facilities, design reference missions (DRMs), and mission phases (Ref. 5). The lunar DRMs include the Lunar Sortie Crew DRM and the Lunar Outpost DRMs, which include the uncrewed Cargo Altair DRM, the Visiting Lunar Outpost Expedition DRM, the Resident Lunar Outpost Expedition DRM, and the Outpost Remote Operations DRM. The supportability concept for the Lunar Sortie Crew DRM emphasizes the use of redundancy and of high-reliability components that require limited maintenance over the typical 7-day mission. The Altair sortie mission will carry a maintenance toolkit that will be based on the *Orion* capsule toolkit.

The Lunar Outpost will be constructed using a combination of several crew and cargo missions. The LSS elements will be delivered using Altair Cargo Landers, and the crewed mission durations will increase in length depending on the availability of logistics cargo, such as food, water, and clothing. From a supportability standpoint, the key trend is that the availability of outpost resources—such as power, data, communications, launch mass allocation, crew time, and stowage volume—increases over time. The supportability concept must evolve within these constrained resources, and any technology development

effort must strive to reduce resource consumption whenever possible. Another key emphasis is to push commonality between the various elements of the lunar architecture.

The LSS M&R concept is separated into two main operations phases: Nominal Operations and Contingency Operations. During Nominal Operations, the maintenance approach is designed to maximize the functional availability of LSS while reducing the overall supportability burden in terms of logistics mass, volume, crew time for maintenance, and cost. Activities during Nominal Operations will follow a predetermined process and schedule that will be managed by the CxP Mission Operations project. During the Nominal Operations phase, maintenance operations will be performed on a continuous basis by the ground crew, surface crew, and surface robotic assets. Even if the surface crew is not present, maintenance operations could continue autonomously, especially in predictive and proactive maintenance (PdM and ProM), where continuous monitoring of the status of LSS hardware is important, especially prior to crew arrival. The second area is Contingency Operations, which occur when, despite the best efforts to anticipate failures through preventative maintenance (PM) and PdM techniques, a random failure occurs that may or may not threaten the life of the crew. During Contingency Operations, maintenance will be reactive in that the crew will be reacting to an actual hardware failure, the safety of the crew will take the highest priority, and restoring the LSS elements to a functional state in the shortest time possible will also be a driver.

In order to implement the LSS supportability concept, a plan is required for significantly reducing the spares and maintenance cargo resupply from Earth. Ideally, the reductions in spares and cargo mass would come without forcing a significant increase in the consumption of other resources such as crew time, power, and data and communications bandwidth. Because all these resources are intricately linked, the main emphasis of pre-System Requirements Review analysis and tradeoffs will be to determine the relationships between resources and how to best optimize the overall supportability approach to achieve the best balance between them.

The approach is an evolutionary path that began with the current ISS Support Program and will culminate in the 500-day Mars Mission. Currently, the ISS Support Program focuses on LRU-level R&R procedures that are designed to minimize the amount of crew time required for maintenance. In the ISS plan, failed LRUs are replaced on orbit, returned to Earth on the shuttle for refurbishment, and reflown later. After the shuttles are retired, it will become increasingly difficult to return ISS hardware to Earth for refurbishment. Although this has already caused an increase in ISS operations costs because of the need to buy new spares, it will help to prepare for LSS operations since there will be a new emphasis on repair and in situ diagnostics, test, and root-cause fault assessment.

The LSS supportability concept involves the steps necessary to reduce spares and maintenance cargo mass, and is separated into phases including the initial ISS Support phase using the shuttle as the primary resupply vehicle (ending in 2010); the ISS Support phase beginning with international vehicle support only and then introducing *Orion* and commercial orbital transportation system vehicles as they come on line (2010 to 2016+); initial lunar orbital flights and Altair sortie missions to the Moon (Human Lunar Return in 2021); and the Lunar Outpost Phase (beginning in 2020 and separated into the three subphases of Construction, Permanent Human Presence, and Mars-Forward). Finally the Mars Mission phase will begin notionally around 2030. In each of these phases, steps are necessary to approach the end goal of a self-sufficient outpost.

The supportability lessons learned during lunar operations will help to drive requirements for the future Mars missions and to fine tune the technologies required for outpost self-sufficiency. The entire structure of the LSS supportability concept is designed to pave the way for the future exploration of Mars and other destinations. For the Mars Mission, NASA is planning on having one crew and one cargo mission to support a 500-day stay. The Mars Cargo Lander will pre-position critical cargo, which will include not only the spares and maintenance equipment but also scientific exploration cargo, including rovers and other elements, life-support gases, crew food and clothing, and everything else necessary to sustain life and support exploration. The Mars crew will have to maintain the hardware elements with little support from Earth and strict limits on launch mass and volume. Appendix D provides a more extensive discussion of supportability for missions beyond Earth orbit.

5.0 Lunar Surface Systems Supportability Needs

Some LSS M&R needs can be derived from high-level CxP documents. Since repair technologies involve details at the component level, lower-level-capability documents will be used whenever available. In a recent technology prioritization plan for ETDP, the LSS diagnostics, test, and verification (DTV) and M&R capability needs were ranked 6 and 7 on the LSS priority list. At the time that this roadmap was developed, LSS was still in the architecture development stage and elements were not decomposed below a system level. The Surface Architecture Reference Document (SARD) captures the ground rules and assumptions for scenario development and scenario operational concepts. Although not explicit requirements, these can be used to anticipate capability needs.

At this early stage, the project must use experience analogs such as the shuttles and ISS to anticipate LSS needs. This includes experience from the NASA ISS and Space Transportation System (space shuttle) logistics depots for lessons learned. The recently completed studies by the Component-Level Electronic-Assembly Repair (CLEAR) project determined the types of electronics used on the ISS and the types of problems experienced. They provide an analysis of ISS electronics and contribute to the body of supportability experience and lessons learned.

Lunar missions require LSS to adopt a supportability strategy that is distinctly different from the ISS. ISS and LSS differ dramatically in the types and intensity of activity. LSS will involve more frequent EVAs and more physically intensive operations with severe wear and tear and physical risks. LSS is also composed of independently mobile elements that increase the odds of accidental damage.

5.1 Needs From the Lunar Surface Systems Surface Architecture Reference Document

Many of the needs, or derived needs, for LSS M&R can be found in the SARD. The SARD is being established by the LSS Architecture Team as it develops scenarios or DRMs to evaluate various vehicle and crew configurations. The document includes ground rules and assumptions to help establish the boundaries of the architecture tradeoff space. The SARD ground rules explicitly or implicitly affect the supportability strategy. The ground rules and assumptions related to supportability are interpreted in terms of supportability capability needs.

The plan for supportability beyond Earth orbit is discussed in more detail in Appendix D. It establishes that logistics beyond Earth orbit needs new capabilities to achieve program supportability and affordability. Unlike prior plans, this plan involves minimizing logistics dependence rather than growing a logistics infrastructure. The objective is to establish a high level of resource independence which, in turn, requires a new capability strategy.

5.2 Needs Assessment Using the International Space Station Analog (Electronics)

The CLEAR project was aimed at developing repair techniques that would enable crews to perform effective component-level replacement of faulty electronics (Ref. 6). This earlier work examined the fundamentals of the basic soldering process in low gravity. It also considered the range of capabilities from basic manual soldering up to an automated apparatus capable of repairing circuits with the latest generation of high-density integrated circuits. These capabilities would be flanked by capabilities to perform diagnostics and tests in support of the repair. The capabilities would need to fit within the payload, resources, and crew time constraints of the program.

The work was based on following premises:

- (1) In many spacecraft electronics assemblies, a major portion of the mass is the enclosure (up to 60 percent).
- (2) An individual electronic component may weigh between 1/100th and 1/1000th of a complete ORU.
- (3) Hardware faults are ultimately repaired at the component level.
- (4) Most components in faulty electronics assemblies are good.

There are opportunities to reduce logistics mass if diagnostic and repair capabilities can be made compact. The CLEAR project demonstrated that solder repairs are feasible in low gravity, given the appropriate tools and crew training. The project’s assessment of CxP in-space electronic diagnostics and repair needs was based on the only practical analog, the ISS. The project examined electrical system drawings and documents from the ISS Vehicle Master Data Base to determine specific materials and processes needed to perform electronic repairs. Furthermore, it considered diagnostic and functional test needs.

Rather than simply tally up the conventional equipment, the strategy was to examine the signal measurement needs and develop a diagnostic and test concept around that information. The study considered the two broad categories of analog (linear) and digital electronics.

Analog electronics encompass all nondigital devices used in instrumentation, power modulation, audio, transducer and motor drivers, and radio communications. The analog signals for LSS are expected to be similar to the ISS signals. Figure 1(a) characterizes the analog electrical signals of ISS electronics on the basis of three variables: bandwidth, channel count, and dynamic range. Figure 1(b) characterizes the digital signals of ISS electronics on the basis of two variables: clock speed and channel count. Digital circuits may involve complex functions, but the signals are inherently simple.

Analog signal measurements cover a very broad range of signal types that are difficult to diagnose by embedded techniques and thus require external diagnostic equipment. To minimize the payload penalty, a synthetic instrument (SI) approach is recommended. SI employs a single vastly reconfigurable instrument set that provides the capability to emulate (synthesize) many different instruments on demand.

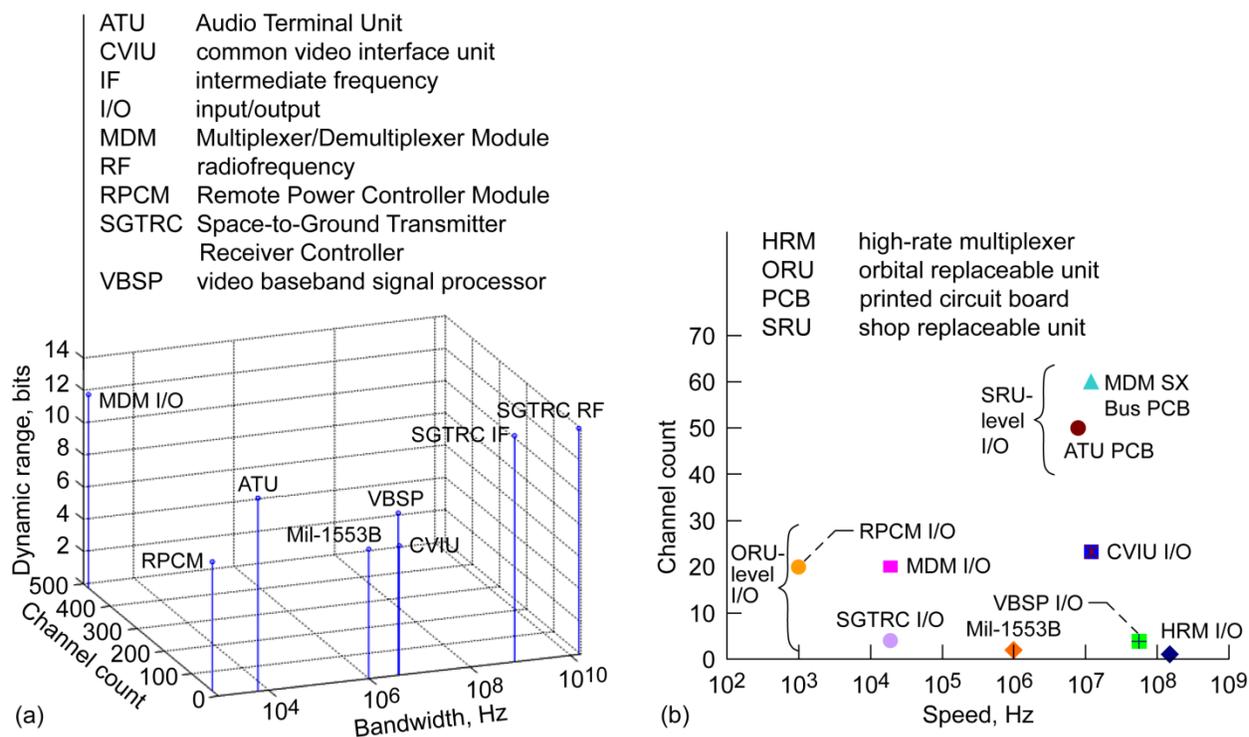


Figure 1.—Gamut of International Space Station avionics signal measurement needs.

Digital devices are inherently suited for internal BIT capability. Embedded, or built-in, diagnostics reduce the need for external equipment and have little or no impact on weight and volume. The recent trend is toward embedding prognostics at the silicon level to monitor the time-dependent degradation that eventually results in an EOL failure. Embedding this type of prognostic capability could extend the life of electronics and reduce dependence on preemptive replacement.

5.3 International Space Station Electrical Problem Reporting and Corrective Action Analysis

To address the types of electrical problems and how often they occur, CLEAR examined the on-orbit electrical problem reports described in the ISS Electrical On-Orbit Problem Reporting and Corrective Action (PRACA) Database. The intent was to determine the percentage of problems that could benefit from diagnostics and the percentage that would involve component-level repair. Roughly 770 ISS on-orbit PRACA reports were recorded through March 2008. Of these, 328 were problems associated with electrical systems. Patterns that emerged from the on-orbit PRACA reports suggest certain shortcomings in the current system.

Despite the widespread use of BIT capability, there were numerous cases of ambiguity about the root cause of a fault. The study concluded that these BIT capabilities do not extend to the component level where the faults actually occur. Because of the ORU R&R strategy, the expense of embedding BIT capability much below ORU level was deemed to be unnecessary. Once a faulty ORU is removed, the root-cause investigation is deferred until the item is returned to Earth. This is contrary to the ProM approach outlined in Appendix C. For LSS, there is no option to return faulty equipment to Earth, and thus the root-cause analysis drives the need for component-level diagnostics by embedded or external means.

Some ISS problem reports involved hardware that simply exceeded its expected EOL. Most EOL hardware faults were in the ISS light fixtures (66 PRACA reports), which is considered to be a logistics problem rather than a reliability problem. The logistics solution is to perform preemptive replacements, which increase the logistics burden by forcing the premature retirement of operating hardware. This implies the need for embedded prognostics to indicate the onset of EOL failures and even indicate the remaining life. Embedded prognostics would maximize service life and minimize preemptive maintenance and logistics.

The study concluded that roughly 63 percent of the electrical problems would benefit from additional diagnostics, particularly for root-cause analysis, and about 42 percent of the problems could be ultimately resolved by a component-level replacement. Many problems were related to operations or software, not hardware; therefore, diagnostics is needed more often than a repair. For LSS, where ground-based servicing is nonexistent, diagnostics that can provide insight to the lowest levels is essential to minimizing effort and driving directly to the root cause.

5.4 Capability Needs Categories

LSS evaluation of technology priorities ranked the DTV and M&R categories as sixth and seventh out of many other technology categories. However, scavenge and recycle (S&R) continues to grow in importance as the lunar architecture studies consider scenarios to reduce costs.

5.4.1 Diagnostics, Test, and Verification

DTV addresses the need to diagnose and test a wide variety of potential electrical and mechanical system problems. Effective repair requires initial diagnosis and knowledge of the root cause. Test and verification are required to verify that repaired hardware is truly functional and suitable to be returned to service.

5.4.2 Maintenance and Repair

Roughly half the problems on the ISS involved electrical system problems. Most electrical problems can be traced to faulty components that can be simply replaced. For practical reasons, spacecraft mechanical and structural hardware tend to have little or no redundancy. Often there are no spares, particularly, for larger components. Performing an in situ repair of major mechanical or structural components may be the only option on the Moon. Unlike the space station, LSS will have substantial wear and tear problems.

5.4.3 Scavenge and Recycle

S&R capabilities are growing in importance as LSS tries to maximize the effectiveness of lunar payloads and minimize program cost, particularly when the Lunar Outpost is established. In lieu of a robust logistics system and to address the uncertainty regarding access to in situ materials, the expended descent section of the Altair Lunar Lander is considered to be a likely resource for hardware and materials.

6.0 Supportability Strategy for an Affordable Sustainable Program

The Vision for Space Exploration involves an expansion of capabilities, but NASA budgets are not expanding to match. These budget constraints require NASA to keep programs affordable and sustainable because once a capability is in place, the ongoing operational cost will be a constraint to future capabilities. This has been the experience with the space shuttle and the ISS, where the operations cost of the established capability has limited the ability of NASA to pursue its next objective. There is concern that a lunar outpost will likewise restrict the future of space exploration. The technologies that support the Lunar Outpost must minimize support cost while providing a high return on investment. A high return on investment will not only help reduce constraints on future programs but may also reduce the costs of Mars exploration. This section defines a strategy that considers the overall goal, as well as the constraints, lessons learned, and needs determined in Sections 2.0 to 5.0.

6.1 Strategy: Resource Independence

This strategy involves developing capabilities based on technologies that can reduce or eliminate dependency on imported hardware, material, and operational resources. It exploits the environment and the material properties and behaviors in the lunar environment. The resource-independence strategy involves building capabilities that achieve a high level of logistics resource independence and minimize the cost of sustaining operations.

6.2 Low-Consumable Dependencies

The lunar environment can be considered to be a resource that can be used to reduce process support needs. For example, soldering and welding repair operations can be performed in a vacuum without flux agents by exploiting the lunar environment and employing technologies that can preclean a surface without consumables. Reducing dependency on a critical process consumable also reduces risk. If the supply of a consumable was exhausted, the process would be halted and the capability would be lost. This may cripple a crew's ability to repair a problem—with the possible loss of capability or even loss of mission. Process technology that is not bound to a complex set of logistic consumables is innately robust.

6.3 Resources From Scavenging and Recycling

In the long term, many materials could be extracted from the lunar surface by in situ resource utilization (ISRU). In the near term, however, portions of the lander could be scavenged and reused for spares or secondary applications. Scavenging could be done at various levels of assembly from LRU to component, and even the raw materials could be scavenged or recycled for various applications.

6.4 “Vitamin” Logistics

The term “vitamin technology” was coined to describe an approach to lunar logistics where payload mass is minimized and value is maximized by importing small amounts of high-value technology and combining it with low-value in situ materials and technology (Ref. 7). This is based on an analogy from biology where the bulk consumption of foods is augmented with small amounts of essential vitamins to ensure health. It addresses the reality that the capabilities of independent operations still benefit from importing small amounts of vital materials. Focusing costly logistics payload capacity on high-value technology and materials while exploiting the low-value bulk materials available from S&R and in situ sources could make logistics much more effective. A microprocessor or field-programmable device could be considered to be a vitamin technology. Furthermore, a high-value vitamin material could be an alloying element or special plating material that greatly enhances the properties of simple bulk material.

6.5 “Bootstrap” Capability Expansion

Certain technologies are attractive because they are versatile enough to expand capabilities in a bootstrap approach. A bootstrap capability provides the flexibility to exploit resources and expand its initial capability. Such a technology can convert hardware and materials into new products. An example could be a technique that can convert scavenged hardware into simple resource-gathering tools. Other examples include technologies that can build fixtures that aid in fabrication and repair, that construct structures that support energy collection, or that convert surplus tanks and logistics modules into LSS depot applications.

6.6 Capabilities Consistent With the Resource Independence Strategy

The supportability lessons learned, supportability capability needs, and the resource-independence strategy can be distilled into general technology characteristics that best meet the needs.

- ***Ease of use:*** Results in low demand for crew, operations, and engineering support resources (operational effectiveness)
- ***Lunar environment compatibility:*** Reduces containment needs and resource consumables; maximizes utility in the lunar environment
- ***Resource effectiveness:*** Minimizes dependence on logistics resources and maximizes exploitation of available or in situ resources
- ***High utility:*** Provides or supports a wide variety of applications, including bootstrap expansion
- ***Risk impact:*** Reduces risk or empowers the crew to effectively respond to risk

6.7 Impact of Scavenging and Recycling on Supportability

S&R improves the return on investment of supportability by making it more deterministic. That is, DTV and M&R technology normally sits and waits for something to break, whereas the technology employed as part of S&R operations will have specific roles. DTV will be used to assess the initial serviceability of the scavenged hardware, evaluate repairs or modifications, and perform functional tests to verify that the hardware is suitable for service. The M&R equipment will be used directly in assembly and repair or reconfiguration of scavenged hardware. Scavenging thus provides specific and scheduled roles for the technologies and places a quantifiable value on the supportability technology. Scavenging disconnects the supportability technologies from the uncertainties regarding repair needs.

6.7.1 Hardware Scavenging

Hardware scavenging involves extracting serviceable hardware from the Lunar Lander or other spent flight hardware. The priority is to employ scavenged hardware as spares. The hardware spares can be acquired at various levels: LRU, SRU, or component. The next priority is to reuse hardware for secondary applications including the bootstrap expansion of outpost infrastructure and a potential LSS depot capability.

Hardware scavenging has an impact on DTV needs. DTV technologies can be used for diagnostics and evaluation of scavenged hardware, and functional test and verification of scavenged hardware prior to reuse. Hardware scavenging also has an impact on M&R needs. M&R capabilities support the disassembly of LRUs for lower-level spares that can be used in the repair and reconfiguration of hardware.

6.7.2 Materials Scavenging and Recycling

Materials extracted from landers, logistics modules, and reclaimable waste can be used for repair and fabrication, and materials extracted from landers can serve as feedstock for repair and fabrication. This drives the need to embed scavengeability into hardware and materials selection. Materials S&R is a primary driver of advanced process technologies including electron-beam- (E-beam-) and ion-beam-based processes.

A Mars mission will be highly dependent on material recycling, and the proposed resource-independence strategy of the Lunar Outpost will demonstrate material-recycling technologies. It should be noted that materials recycling has drawn significant attention in recent years. The LSS S&R technologies may have important environmental, social, and economic spinoff potential as “green technologies” that may provide a tangible return on investment for terrestrial applications.

6.8 Derived Supportability Capabilities

Table II lists the capabilities derived from lessons learned, interpretations of LSS documents, and needs described in Sections 2.0 to 5.0. These capabilities are the primary goals of the supportability technology development.

TABLE II.—SUMMARY OF DERIVED SUPPORTABILITY CAPABILITY NEEDS

Capability need	Rationale
Embedded diagnostics and prognostics at lowest levels in electronics	Many International Space Station “root-cause unknown” entries resulted from lack of an ability to identify and isolate a fault below the orbital replacement unit (ORU) level. Component-level embedded diagnostics, test, and verification (DTV) reduces the need for, and the payload penalties of, external instruments.
Synthetic instrument (SI) approach when embedded diagnostics not feasible	Certain circuits have signals or support dependencies that are not effectively addressed by embedded techniques. SIs are intended to minimize the instrument payload penalties of large conventional test equipment. It exploits advances in field-programmable gate arrays (FPGAs), and signal manifold technologies.
Embedded structural fault-detection and fault-location system	Flight-weight structures are highly stressed and designed with narrow margins. These structures are not damage tolerant, and lives may depend on quickly detecting, locating, and repairing a fault.
Conductor and connector fault-detection and fault-isolation, and signal rerouting	Conductors (cables and connectors) are a significant source of electrical problems and are vulnerable to operational and environment damage. Conductors in complex harnesses are difficult to repair. Emerging techniques called signal manifolds can actively redirect signals through alternative paths around the damaged conductor.
Diagnostic radiofrequency identification (RFID), fluid, and electrical line locator	Cable harness and fluid line repair involves locating a specific line among many, is time consuming, and is prone to risk of further damage. RFID tags can be used to quickly locate a specific line at key access points, thereby minimizing disruption and risk.
Remote in situ calibration	DTV and repair equipment must be properly calibrated. Without an option for returning equipment to Earth for calibration, remote or in situ calibration is the only viable option.
Accessible enclosures for ease of assembly, diagnosis, and repair with minimum loss of integrity	Space systems are difficult to access for diagnostics and repair. An enclosure that unfolds to allow diagnostics and test without violating system integrity dramatically simplifies repair operations. It is also highly applicable to scavenging.

TABLE II.—SUMMARY OF DERIVED SUPPORTABILITY CAPABILITY NEEDS

Reconfigurable electronics	Reconfigurable electronics allows us to use scavenged hardware as spares to reduce logistics.
Component reparability and scavengeability	In situ repair is viable if the materials selected are suited to repair and can be scavenged and reused with minimum processing.
Noncontact measurement	Measurements made by noncontact optical methods support diagnostics and repair with a minimum set of instruments. Noncontact methods also avoid damage and wear in harsh process environments.
Metal weld repair	Major structures are not supported by spares and must be repaired in situ. Electron beam technology can weld repair cracks, rejoin or reinforce broken metal hardware, and even upgrade utility with weld-on features.
Material cutting and sizing	Repairs that exploit scavenged materials require cutting and trimming techniques suitable for extracting a variety of materials of varied shape and size. Lunar Surface Systems will need techniques that do not require massive equipment or consumables.
Manual and automated electronic component repair	Electronics assemblies are almost entirely built by solder processes. Depending on complexity, solder repairs may be done manually or by automated equipment.
Surface repairs; in situ restoration of damaged hardware surfaces	Many mechanical faults involve damaged surfaces. Surface damage in flanges and hatches causes leakage. Rotating shafts, bearings, and motors are vulnerable to surface damage. Repair must also treat surface properties: hardness, corrosion resistance, and conductivity.
Materials scavenging, recycling, and fabrication; feedstock generation	Scavenging materials and reusing them requires converting the reclaimed material into a suitable feedstock that is versatile, thereby minimizing the equipment mass and material logistics infrastructure.
In situ fabrication capabilities	Exploiting scavenged or recycled materials requires a space-compatible fabrication process that can produce usable end products with little or no process consumables and no postprocessing.

6.9 Embedded and Process Capabilities

M&R is commonly viewed as involving external processes. However, there are many opportunities to embed a capability into hardware. If as much capability as possible is embedded into the design of the flight hardware, the program can minimize the up-mass of external equipment. Furthermore, the features that ensure that hardware is repairable by in situ processes must be done in the initial design. Therefore, embedded and process technologies are codependent, and the development of one influences the other.

Process and embedded technologies, which have different development criteria, are addressed in the following sections. These lower-level criteria will be consistent with the development strategy and will be used to screen the initial set of technologies and in down-selecting candidate technologies. The criteria will be balanced so that negative and positive aspects keep the evaluation simple and minimize the need for weight functions. Criteria will need to be reviewed and refined by stakeholders. In many cases, the selection criteria may also serve as the basis for the key performance parameters that are used to monitor the progress of the technology development.

6.10 Technology Infusion

In general, Technology Readiness Levels (TRLs) as defined by NASA have nine levels. At TRL 6, a technology has been demonstrated in a relevant environment and is considered to be mature enough for infusion into a space flight program (Ref. 8). The current schedule shows that the first Altair vehicle will fly in 2021. Technology for Altair must be at TRL 6 by the time that the Preliminary Design Review (PDR) is complete. Although the criteria for selecting a capability are driven primarily by needs, there may be multiple technology options available. Technology selection requires further criteria that consider needs in a context of constraints or operational drivers, such as size, weight, and power; crew operations; and training (Ref. 9). These criteria are identified in Sections 7.0 and 8.0 and will be used to evaluate the candidate technologies. The criteria will be further refined and technologies will be characterized in the formulation phase by feasibility studies and technology assessments.

The technology development funding for CxP is very constrained, and not all technologies can be funded. All technologies will be screened by a process that involves evaluating the following criteria:

- **TRL (1 to 9):** This criterion considers the technical maturity, where TRL 6 is considered high enough to be passed from technology development to a operational flight system development phase.
- **Mass and power impact:** These criteria consider the impact of a technology on flight systems as a payload or as an embedded feature. Often there is a mass and power penalty that must be traded against the overall life-cycle benefits of the technology.
- **Operational cost impact:** The impact on crew time, training, and life-cycle support cost often offsets the impact on mass and power. Supportability technologies are aimed at reducing operational costs.
- **Risk reduction:** This is the impact of the technology on reducing risk (or response to risk). Supportability technology must empower the crew to address risk that cannot be handled by redundancy alone.
- **Utility:** This criterion is the general utility or usefulness over a wide range of applications.

7.0 Embedded Supportability Technologies

Supportability technologies can be designed in, or embedded into the flight hardware, to minimize the need for external hardware with little impact to weight and power. Embedded technologies, however, impose added development risk in the host hardware and must be integrated into the flight hardware development schedule. Embedded technology should be at a high TRL for infusion into the Altair flight vehicle development path. The development of embedded supportability technologies has a direct impact on the process technology development. In some cases, embedded technologies minimize the need for process equipment; in others, the embedded technologies ensure the effectiveness of the external process technology.

7.1 Embedded Technology Development Criteria

Derived from general needs, lessons learned, and specific assumptions and ground rules from the SARD, this section describes the capabilities or special properties that can be embedded into systems. Sections 7.1.1 to 7.1.8 present the capabilities needed, and evaluations of embedded technologies will consider how well these needs are met. These criteria are intended to ensure that the technologies are consistent with the supportability strategy.

7.1.1 Access for Maintenance, Repair, and Scavenging

Embedded technologies need to ensure that hardware is accessible for maintenance, repair, and scavenging.

Rationale: This includes considering the time effectiveness of manual and automated access with minimum violation of system integrity. Depot and ISS flight experiences indicate that the crew time needed to extract LRUs, hook up equipment, deintegrate, access components, reintegrate, and test assemblies far exceeds the time involved in the actual component repair. This is expected to be the same for scavenging operations. Therefore, embedding features that enhance accessibility and preserve integrity also improves supportability.

7.1.2 Embedded Diagnostics

Embedded technologies need to provide diagnostic capabilities from the system level to the component level.

Rationale: The ISS PRACA report history indicates that the current BIT capability on the ISS provides limited insight into problems below the ORU level. There are a substantial number of “unknown root cause” statements in the ISS PRACA system that currently can only be resolved by returning equipment to the Earth. Component-level embedded diagnostics will reduce external equipment and

speed problem isolation. Furthermore, it will reduce the time and cost of unneeded replacement due to root-cause ambiguity or misdiagnosis.

7.1.3 Embedded Prognostics

Embedded technologies need to provide prognostics capability from the system level to the component level. Space environment effects and aging will cause degradation to occur over time in electronic systems. Detecting time-dependent degradation and predicting EOL will preempt catastrophic failures yet maximize life.

Rationale: Component-level embedded prognostics reduce external equipment, reduce ambiguity, and speed problem isolation. Prognostics are aimed at detecting time-dependent (aging effects) that will ultimately end the life of otherwise reliable hardware. Along with environmental effects, EOL depends on variations in the original manufacturing and service life history. The preemptive time-based maintenance approach means that the service life is cut short. Embedded prognostic devices can track life experience by sharing the same experience and same degradation environment. Specific internal indicators can be used to alert the system and to predict an EOL failure. Thus, as a form of condition-based maintenance, prognostics eliminates the need for wasteful preemptive replacement without the risks of running the system to failure.

7.1.4 Common Components and Interfaces

Embedded technologies need to provide a high level of commonality that minimizes M&R equipment needs, operational resources needs, and the number of component spares required.

Rationale: Commonality has elevated importance when flight components are scavenged as spares. The ability to repair with scavenged components will depend on the ability to transplant components from one system to another.

7.1.5 Adaptable, Reconfigurable Hardware

Embedded technologies need to provide flexibility or innate reconfigurability to support applications beyond the original flight function.

Rationale: Reusing flight hardware may require reorganizing internal functions or combining basic functions with other hardware (and functions) to provide new capabilities. This has implications for software and interconnection designs. In some cases, the adaptability can be seen as an alternative to imposing physical commonality.

7.1.6 Scavengeable Components

Embedded technologies need to be able to safely extract components and reuse them without substantial loss in reliability.

Rationale: Scavenged components intended as spares will still need to provide a high level of reliability. Designers will need to consider how best to mount a component so that it can be extracted, stored, and reused as a spare or for new applications

7.1.7 Scavengeable, Recyclable Materials

Embedded technologies need to provide materials that are compatible with the lunar environment and that can be scavenged and recycled with a minimum set of processes.

Rationale: The success of the supportability strategy depends on developing lunar-compatible materials and processes that do not require massive equipment or imported process materials. This means limiting the choice of materials, which may affect vehicle payload performance. The tradeoff between maximum performance and reusability must consider the supportability impact.

7.1.8 Deratable Design for Repaired or Scavenged Hardware

Flight hardware must be able to operate in a derated mode to allow scavenged or repaired hardware to operate under less stress and provide extended useful life.

Rationale: Repaired and scavenged hardware cannot be as thoroughly tested as the original acceptance tests; thus, there is uncertainty about reliability. Designing hardware to operate in a derated mode lowers stress, adds margin, and improves reliability and operational life.

7.2 Embedded Capability Categories

In Figure 2, the three main capability categories in embedded technologies are further decomposed into capability subcategories. The capability needs are defined for each subcategory, and candidate technologies are briefly discussed. Note that in some cases the subcategories are better described as hardware or material properties rather than capabilities.

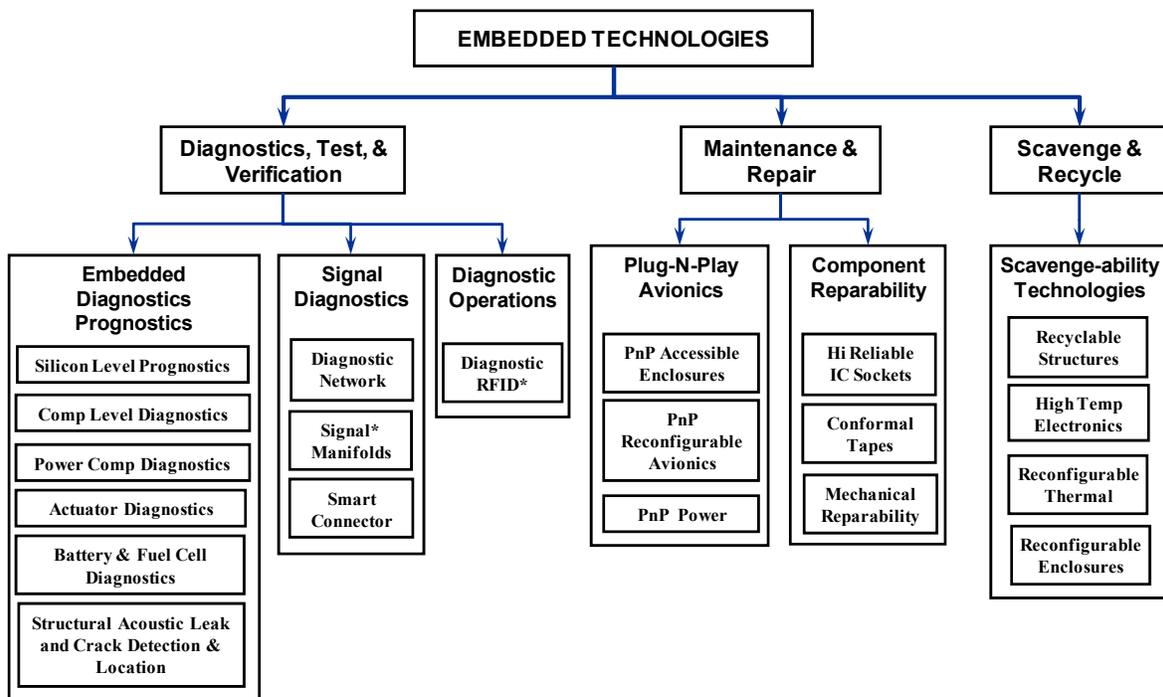


Figure 2.—Embedded technologies needed for Lunar Surface Systems supportability. RFID, radiofrequency identification; IC, integrated circuit.

7.2.1 Embedded Diagnostics and Prognostics

This capability provides diagnostic and prognostic capabilities from the ORU level to the component level. The techniques can assist in detecting and isolating faults and problems that evade system-level detection. Furthermore, new techniques permit the prediction of the ultimate EOL at the silicon level for electronics. For large structural components, techniques are needed to help the crew detect and locate dangerous cabin leaks and potentially catastrophic structural cracks.

Silicon-level prognostics: Embedded in electronics, features at the silicon level serve as “canary devices,” providing an early detection of age-dependent degradation, and indicate the onset of an EOL failure. By providing an accurate measure of remaining life, the program can extract more useful life without relying on preemptive maintenance that would normally replace hardware well in advance of failures on the basis of statistical life prediction rather than actual life prediction (Refs. 10 and 11).

Component-level diagnostics: Embedded in electronics, techniques that detect lead cracking in large integrated circuit packages, such as very large ball-grid array (BGA) packages, have been introduced to detect transients caused by solder joint cracking that may affect a small portion of the many connections. Many modern devices could exploit the technique and use it to reroute signals to unbroken spare connections (Ref. 12).

Power-component diagnostics (prognostics): A so-called ring-down technique can be used to expose the degradation of power components by exploiting changes in the resonant characteristic of discrete power devices. The technique can identify the specific device and speed diagnostics and replacement (Ref. 13).

Actuator diagnostics (prognostics): This technique exploits the interaction between an electro-mechanical device (motor-actuator) and the power-drive electronics. Changes in actuator or motor condition will alter the response to drive inputs. The health of the drive circuit and electromechanical actuator are monitored.

Battery and fuel-cell diagnostics: This technique monitors the health of electrochemical energy storage devices. Chemical energy storage assemblies tend to be very heavy. These technologies can facilitate the replacement of individual faulty cells and minimize the need to replace entire assemblies.

Automated leak location: This technology employs structural acoustic sensor networks for detecting and quickly locating cabin pressure leaks. The technology may dramatically reduce response time and loss of critical resources.

Automated crack detection: Similar to automated leak-location technology, an array of structural acoustic sensors may be used for detecting structural cracking, which may be very useful for pressurized mobility equipment. This technology may be able to share some of the same system elements as automated leak-location technology.

7.2.2 Embedded Signal Diagnostics

Diagnosing and testing of hardware is often impeded by complex connectors and wiring harnesses and the need to build custom test adapters for each application. Analog wiring is particularly troublesome because each line may have unique signal properties and be susceptible to interference and loss of signal integrity. There are multiple options for working around this problem. Converting analog signals to digital reduces sensitivity to interference and allows data to be sent via high-speed serial data links that use standardized interconnections and interface protocols.

Replacement of analog wiring bundles with standardized digital networks with so-called PnP features allows rapid deintegration and reintegration of hardware with minimum support equipment. This extended portability is particularly important for scavenging and reusing flight hardware. The recently developed Smart Transducer Interface Module (STIM) and internal Transducer Electronic Data Sheet (TEDS) extend the benefits of networking flexibility down to the individual device level.

Many electronic problems only appear when the units are physically interconnected and operating. Often it is necessary to attach multiple instruments to observe signals. In some cases, it is necessary to

inject a stimulus signal and observe a response. This complexity can be minimized by embedding flexible interconnection technology that provides the ability to tap into signals between units without violating system integrity or distorting signals.

Diagnostic networks: This technology embeds networking at the transducer level and provides a means to reconfigure avionics to isolate devices and perform ad hoc in-circuit testing. It employs new IEEE 1451 “Smart Transducer Interface Standards” where each device includes a Network Capable Application Processor, a STIM, and an embedded TEDS (Ref. 14).

Smart connector: This technology developed by the NAVAIR program provides signal monitoring of integrated systems and reduces the number of specialty test connectors while reducing fault ambiguity. It may be further enhanced if combined with the signal manifolds technology, described next. In addition, smart connectors may provide a means of instantly sensing and isolating faults. This capability is very useful in protecting a system whenever a new or repaired unit is installed that cannot be fully tested outside the system.

Signal manifolds: This technology, which was introduced by the U.S. Air Force PnP Satellite program, provides automated signal routing that is intended to simplify avionics integration. Employing microelectromechanical systems (MEMS) technology, the signal manifolds technology allows for remote signal routing without physically intruding into the system or violating system integrity. The connection flexibility also allows conductors to be tuned to desired impedance specifications by connecting lumped parameter tuning elements on command (Refs. 15 to 17).

7.2.3 Embedded Diagnostic Operations

These capabilities address the physical aspect of diagnostics and repair operations. Locating and repairing faulty wires, components, and fluid lines is impeded by the large number of lines packed into spacecraft and the ambiguous markings used.

Diagnostic radiofrequency identification (RFID): Embedded RFID tags can assist in the physical location and replacement of the correct components or lines and even provide ancillary data to support tests (Ref. 18).

7.3 Embedded Maintenance and Repair Category

7.3.1 Plug-and-Play Avionics

This is an adaptation of capabilities developed by the AFRL as part of the PnP Satellite Program that employs multiple technologies to rapidly integrate a satellite in 6 days. The capabilities combine structural, avionics, and power accessibility in one design. PnP avionics includes enclosures with integrated hinged walls, where avionics boxes can be literally unfolded without disconnecting or violating the system integrity. It includes PnP self-organizing network connections. It also involves power utilities that are embedded in both the network connections and the structure. This can have profound implications to the supportability of flight hardware and can enable field repairs with minimum reliance on external equipment. Further development is needed to adapt these technologies for fault-tolerant, human-rated applications.

PnP accessible enclosures: These are highly accessible enclosure assemblies with unfoldable or hinged structural joints. This structure allows the integrator to structurally unfold the enclosure so that it can lay flat for ease of access. This approach also minimizes the violation of electrical integrity by maintaining electrical connections. The unit is still able to function in this condition, which minimizes retesting (Ref. 19).

PnP reconfigurable avionics: This PnP network automatically configures the connection and reads the IEEE 1451.0, Smart Sensor Electronic Data Sheet. The intent is to enable integrators to alter,

reconfigure, or add new capabilities to the system while minimizing the software overhead. The approach is much like the PnP capabilities provided by a personal computer universal serial bus (USB) port (Ref. 19).

PnP embedded power: This technology embeds power distribution ports in enclosure structural panels. In effect, the panels are prewired for power alongside network connections. It provides further flexibility that supports hardware scavenging and reuse in new applications (Ref. 20).

7.3.2 Electronic Component Reparability

This need involves developing components that are designed to permit field repairs with minimum processing. It includes eliminating features that impede access, removal, and reinstallation of components. It could include developing a removable conformal tape that could eliminate conformal coatings used on electronics. It also includes reintroducing the use of integrated circuit sockets designed to be vibration and shock resistant and providing a near tool-less method of replacing integrated circuits.

High-reliability integrated circuit sockets: Repair of electronics can be dramatically simplified by integrated circuit mounting sockets. This is particularly true for large-scale devices with connection counts that exceed 2000 pins. The sockets allow replacement of integrated circuits with a minimum set of tools and may eliminate the complexity and risk of soldering large BGAs (Ref. 21).

Low-electrostatic-discharge (ESD) conforming tapes: Simple, low-ESD conforming tape permits removal and reapplication of conformal protection without physical damage or hazardous chemicals. This tape could be derived from high-temperature, low-ESD tapes used in circuit fabrication (Ref. 22).

7.4 Embedded Scavenge and Recycle Category—Scavengeable Material Technologies

Technologies in this subcategory involve embedding properties that support S&R capabilities. They improve hardware and material scavenging by either simplifying the scavenging process or by improving the reusability of hardware. For materials, S&R implies selecting materials that can be processed in the lunar environment. For example, high-temperature electronics are intended to address the reusability of scavenged electronic components by eliminating the need for a central thermal control system.

Recyclable structures: Structural materials must be recyclable by processes compatible with the space environment. Metals are the preferred material for recycling.

High-temperature electronics: High-temperature tolerance eliminates or reduces the need for heat sinks and cold plates and may eliminate the need for a central thermal control interface and improve portability. Materials such as silicon carbide, silicon germanium, and silicon on insulator are likely candidate technologies.

Reconfigurable thermal control: Removable, reconfigurable avionics thermal control will provide portability and less dependence on centralized active thermal control. This may involve the use of sealed heat pipes to eliminate fluid connections.

Reconfigurable enclosures: This is an extension of PnP avionics that involves developing avionics enclosures that can be decomposed into panels and reused to create new avionics assemblies. Flexibility is further enhanced by embedding data networks and power connections similar to the Air Force PnP Satellite Program (Ref. 19).

7.5 Embedded Technology Preliminary Evaluation

Table III shows a preliminary characterization of the technology candidates in terms of technology infusion. This can be considered to be an initial screening based on the parameters described in Section 6.0. In the mass, power, and crew time columns, the technology may have no impact, a low, medium, or high impact, or it may reduce the mass, power, or crew time.

TABLE III.—EMBEDDED TECHNOLOGY PRELIMINARY CHARACTERIZATION

Technology	TRL ^a	Mass	Power	Crew time	Risk reduction	Utility
Silicon-level prognostics	5	None	None	Reduce	Predicts end of life (EOL), enables in situ root-cause analysis	Prediction of remaining life
Component-level diagnostics	5	None	None	Reduce	Enables in situ root-cause analysis	Self checkout
Power-component diagnostics	4	Low	None	Reduce	Predicts EOL, enables in situ root-cause analysis	Prediction of remaining life
Automated leak location	4	Low	Low	Reduce	Enables rapid response to cabin air leakage	Health evaluation
Automated crack detection	2	Low	Low	Reduce	Enables rapid response to structural cracking	Health evaluation
Diagnostic networks	4	Low	None	Reduce	Provide automated isolation and circuit diagnostics	Health evaluation
Smart connector	4	Low	None	Reduce	Reduces ambiguity, prevents repair errors	System evaluation
Signal manifolds	4	Low	Low	Reduce	Enables signal rerouting around failed connections	Flexible applications
Diagnostic radiofrequency identification (RFID)	4 to 5	Low	Low	Reduce	Reduces hardware identification errors, simplifies fault location	Orbital replacement unit log book
Plug-and-play (PnP) accessible enclosures	5	Moderate	Low	Reduce	Simplifies access, reduces integrity violation	Ease of repair and reuse
PnP reconfigurable avionics	5	Low	Low	Reduce	Provides sensor signal-routing	Ease of repair and reuse
PnP embedded power	4	Low	Low	Reduce	Simplifies power integration and validation	Ease of repair and reuse
High-reliability integrated circuit sockets	2 to 3	Low	None	Reduce	Simplifies replacement of electronic components	Ease of repair and reuse
Conformal tape	2 to 3	Low	None	Reduce	Reduces risk in circuit repair	Ease of repair and reuse
Recyclable structures	2	Moderate	None	Reduce	Provide feedstock for repair and fabrication	Ease of repair and reuse
High-temperature electronics	3	Reduce	None	Reduce	Allows passive thermal control	Ease of repair and reuse
Reconfigurable thermal control	3	Reduce	None	Reduce	Enables greater portability and reuse	Ease of repair and reuse

^aTechnology Readiness Level.

The evaluation considers the technology’s role in risk reduction and the overall utility that the technology provides. As embedded technology, the mass and power affect every mission and, thus, must be carefully balanced against the operational, utility, and risk-reduction benefits.

7.6 Embedded Technology Development Cost Considerations

Of the capabilities listed, many involve a distinct technology that is embedded or added to the flight hardware design. In some instances the capabilities can be interpreted as design features or properties that are incorporated with little impact on the overall vehicle development. Some demonstration may be required to validate the TRL. Certain capabilities, such as the AFRL’s PnP avionics technologies or NAVAIR’s Avionics Technology program, may be acquired through a cost-sharing collaboration. Note that the ETDP role in embedded technology development will end when the technology is infused and the flight program becomes responsible for flight development.

8.0 Supportability Process Technologies

Derived from general needs, lessons learned, and specific assumptions and ground rules from the SARD, this section describes the capabilities needed and the technologies intended to meet them. Process technologies are external to flight hardware, and development is driven by end applications. The development schedules for process technology are similar to those for independent payloads and are not expected to be on the flight vehicle development path. As described in Section 7.0, the development of process technology is somewhat dependent on selections made in embedded technology. If there is a technical or program reason not to adopt an embedded solution, then an external process may replace it. In other cases, a process technology may depend on the design materials selection, and changes in materials will directly impact the viability of a specific process.

8.1 Process Technology Development Criteria

Process technology will need to be demonstrated independent of the flight hardware and may include demonstration aboard the ISS. The criteria in Sections 8.1.1 to 8.1.4 are intended to ensure that the technologies are consistent with the supportability strategy. These criteria are defined in more detail in Table IV.

8.1.1 Environment Compatibility Criteria

A process that is compatible with the space environment eliminates the complexities of preserving materials and hardware in space. Environment compatibility minimizes process support and containment equipment and, in turn, simplifies operation and logistics. Consistent with the supportability strategy, developing process technologies that are compatible also reduces resource dependency. Process compatibility is primarily an issue of base material and process material compatibility. Processes that require an atmosphere impose added burdens on the crew cabin environment; instead processes should be selected that are suited to the lunar environment.

8.1.2 Process Dependency Criteria

Process dependency may be defined as the need for external infrastructure, consumable material resources, preprocesses, postprocesses, and equipment, crew or robotic operation support, or dedicated process containment required to perform processes. Dependencies are contrary to the supportability strategy of resource independence. They are also a measure of the process's logistics and operational complexity. A thorough breakdown and description of these dependencies is a system engineering task that is needed for an informed technology evaluation.

8.1.3 Resource Effectiveness Criteria

A supportability strategy that is based on resource independence requires that the resources imported from Earth be minimized and effectively used. In addition, the strategy requires developing capabilities to exploit available resources effectively. As capability builds, the long-term goal is to switch from an entirely logistics-based resource consumption to in situ resource consumption. The use of scavenged hardware and materials from flight systems is a transitional capability that bridges the gap between pure logistics and ISRU.

TABLE IV.—PROCESS TECHNOLOGY EVALUATION CRITERIA SUMMARY

Environment compatibility	
Low gravity	Low gravity has a profound effect on processes dependent on fluids or fluidlike behavior. Although 1/6 g is sufficient to allow liquids to settle in containers, the liquid’s surface tension dominates its behavior.
High vacuum	The ultrahigh vacuum has long-term effects on many materials we use. Polymers in particular will tend to outgas volatile components resulting in a loss of mass and degradation of properties. Repairs with volatile compounds—including reagents, fluxes, cleaning fluids, and liquid coatings must be avoided.
Thermal	The lunar thermal and vacuum environment work in combination to degrade many materials. Outgassing of volatile components is accelerated by the bake-out effects of high-temperatures in a vacuum.
Radiation	High-energy particles pose reliability and crew safety hazards. Intense ultraviolet radiation breaks chemical bonds and continuously degrades familiar polymer materials. Inorganic metals and ceramics are most tolerant of radiation.
Dust	Dust is expected to be a substantial source of equipment wear and tear. The abrasive effects of dust are expected to damage seals in hatches and wear away rotary and linear shaft seals. Compatibility may require eliminating exposed shaft and bearing hardware. Optical surfaces like helmet visors, viewports, and camera optics are very vulnerable to being obscured by dust contamination and damaged during cleaning.
Process dependency	
Infrastructure	A given technology will have dependencies on the Lunar Surface Systems (LSS) resources, including power, thermal control, communications, data systems, and various LSS elements such as robotics. These dependencies will be characterized by quantifiable resource usage values: total, average, and peak values.
Logistics resource	These consumed resources are provided by logistics supplies launched from Earth.
Preprocess and postprocess	This considers the dependencies on processes that both precede and follow the primary process. These preprocess and postprocess activities have their own dependencies and resource needs and contribute to the overall cost of employing a given technology. This may include constructing special temporary fixtures to support a repair.
Operational	This dependency involves the need for crew activity and ground support activity (acting through the crew or robotics). The primary unit of measure is labor hours.
Containment	Containment dependency is derived from environment compatibility criteria. This may include the facilities needed to protect a process from the environment or to protect the environment from the process. Containment dependencies may generate a need for an entire system.
Resource effectiveness	
Common resources	This criterion considers the value of using common resources that simplify logistics. It is particularly important to consider resources that may someday be derived from in situ sources.
Scavenged hardware	Exploiting available surplus flight hardware has a long-term benefit since hardware accumulates over multiple missions. Flight hardware in combination with in situ resources will provide a much higher value than if these resources are considered separately.
Scavenged materials	Hardware can be exploited for its material content if the hardware function is not needed. Often materials can be leveraged by combining with other common materials. For example, a hardware material may be combined with an in situ material to create a new high-value material.
Lunar environment	The lunar environment itself can be regarded as a resource to be exploited. The high-vacuum, low-gravity, intense-radiation, fine-dust environment can serve as a resource for many processes.
Process utility	
Utility across categories	A technology that provides utility across many application categories indirectly reduces complexity and increases commonality. Broad utility allows the technology to serve as part of the infrastructure rather than as an end application.
Extravehicular and intravehicular activity (EVA and IVA) utility	Technologies that support both external (EVA) and internal (IVA) operations reduce the need for a function to be duplicated in different hardware.
Manual, robotic utility	Technologies that can be employed by the crew manually as well as by robotic units provide wide utility while providing operational flexibility.
Bootstrap capability	This is the capability to bootstrap from a relatively small capability and to exploit available resources and capabilities to build a much greater capability over time. This is an investment strategy that minimizes both initial and ongoing operational costs.

8.1.4 Process Utility Criteria

The process utility is intended to select technologies that provide the greatest possible utility from a small set of capabilities in order to achieve the supportability strategy. Process technologies will be

evaluated for their ability to support multiple applications across the DTV, M&R, and S&R categories. The technology also will be evaluated for utility in both IVA and EVA applications. The evaluation assesses the utility as a manual, automated, or robotic process. The utility evaluation of a process determines the potential to expand or to bootstrap an existing capability. For example, technologies that can produce tools can effectively expand capabilities without additional payloads.

8.2 Process Capability Categories

As shown in Figure 3 the three main capability categories in process technologies are further decomposed to capability subcategories. The capability needs are defined for each subcategory, and candidate technologies are shown.

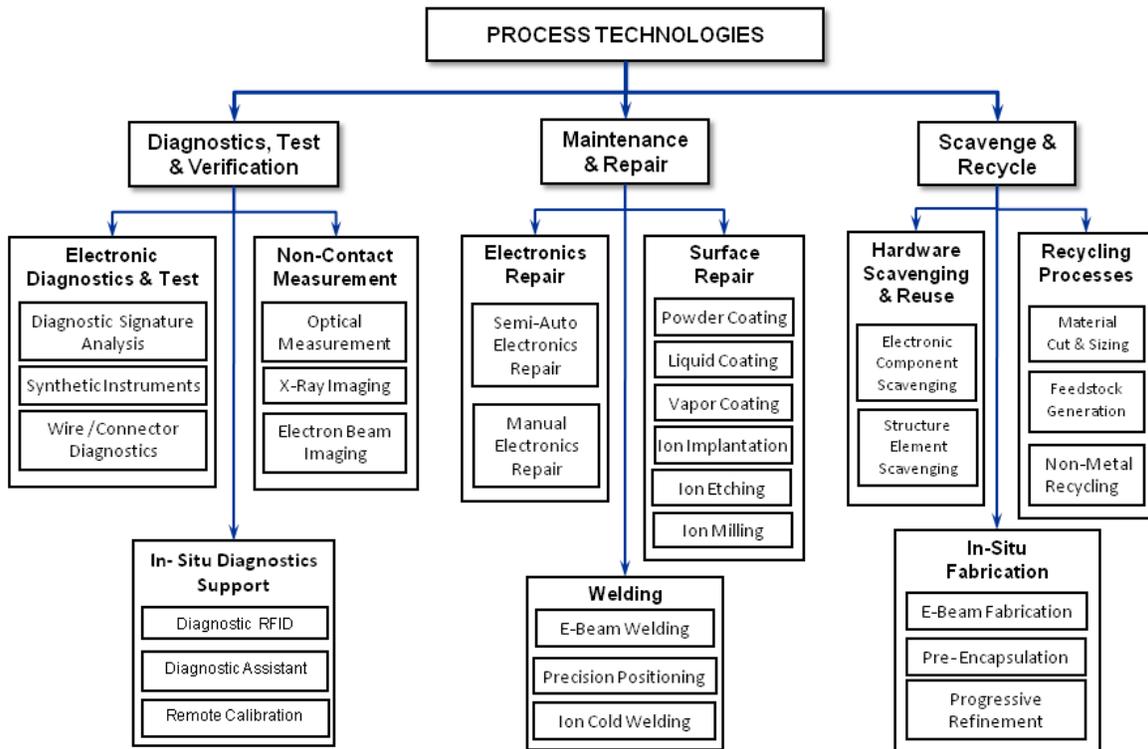


Figure 3.—Process technologies needed for Lunar Surface Systems supportability. E-beam, electron beam; RFID, radiofrequency identification. Many maintenance and repair (M&R) technologies also support scavenge and recycle (S&R) needs.

8.3 Diagnostics, Test, and Verification Process Category

This capability provides the diagnostic and prognostic capability from the ORU level to the component level. The techniques can assist in detecting and isolating faults and problems that evade system-level detection. The technologies shown here are external processes, and in some cases, they overlap the capabilities of the embedded technology. However, process technology is more flexible than embedded technology, with broader application and utility. Process DTV technologies may also serve as backup technologies whenever embedded DTV is rendered inoperative. The selection of an embedded technique will impact the related process technology, but it is unlikely that embedded solutions will eliminate processes entirely. Sections 8.3.1 to 8.3.3 describe the technology candidates for three DTV process subcategories.

8.3.1 Electronic Diagnostics and Test Processes

Technologies in this subcategory are very important because electronics have many built-in functions, and special instruments are the only way to observe these functions. Even mechanical systems rely on electronics for remote command, control, and data acquisition.

Diagnostic signature analysis: Diagnostics based on the graphical trace comparison of a known good signature to a suspect signature allows unskilled users to locate circuit faults. The U.S. Navy uses its analog signature analysis technique in concert with a program that provides users with an updated database of known good signatures for comparison. For NASA applications, the capability will be expanded to include the measurement of complex impedance over a frequency range that can reveal circuit resonant properties. This new complex signature analysis technique expands the range of diagnostic applications and provides a greater capacity for detecting hidden circuit elements (Ref. 23).

Synthetic instruments (SI): This technology replaces conventional diagnostic and test equipment with a highly configurable package capable of “synthesizing” various instruments on demand. Advanced field programmable devices are used to replace the digital functions of conventional instruments. To address the inflexibility of the conventional analog front end, microscale mechanical switching devices are used to reroute signals and adjust the front-end electrical properties to match the analog signal (Ref. 24).

Wire connector diagnostics: This technology involves using combined electrical and physical response to an injected signal to evaluate wire harness and connector integrity. This may include combining electrical time-domain reflectometer techniques with physical (acoustic) test methods (Ref. 25).

8.3.2 Noncontact Measurement

Technologies in this subcategory measure mechanical hardware dimensions and internal material properties. Noncontact, optical, and dimensional measurements and measurements with imaging technologies require fewer tools and do not interfere with the processes they support. They measure key internal properties and can detect hidden flaws.

Three-dimensional optical measurements: Optical measurement techniques are prevalent in automated manufacturing processes, where optical imaging is the dominant method of inspecting and positioning components in high-speed assembly. Optical measurement technology automates and simplifies the process of checking dimensions, particularly in hostile environments. Optical measurements are also useful for inspection and remote assessment of surface damage.

X-ray imaging: X rays can detect internal flaws, measure internal dimensions, and determine material properties. X rays have been used as a nonintrusive investigation tool for mechanical and electrical problems on launch vehicles and are widely used for automated BGA inspections. The technology development will examine methods of enhancing x-ray detector sensitivity to minimize crew radiation hazards.

E-beam imaging: Electron beams have an extreme range of imaging scales and are compatible with the lunar environment. E-beam imaging could be integrated with welding and fabrication technology. Further study is needed to compare the feasibility of E-beam imaging with optical imaging.

8.3.3 In Situ Diagnostics Support

Technologies in this subcategory will assist crewmembers. They include a local node attached to the CxP Command, Control, Communications, and Information infrastructure and diagnostics support. This capability also will include local information libraries and data archives that could support users if communications were lost. The RFID and digital user assistant devices are at fairly high TRLs and should be linked to Altair for early applications. Remote tool calibration warrants further investigation.

Diagnostic RFID: This technology exploits RFID to help identify and track repair hardware and to physically locate and identify faulty LRUs and specific harness cables. It could be deployed as a handheld unit that links RFID tags with an onboard data system (Ref. 18).

Portable electronic diagnostic assistant: This technology is based on a NAVAIR unit that provides the user interface and various maintenance libraries that are automatically synched and refreshed with ground-based sources, including SI programs, hardware manuals, “gold” signature data, and crew training and refresher media. This portable assistant (laptop or personal digital assistant (PDA)) will also provide wireless local area network access (Ref. 26).

Remote calibration: Calibration is a supportability infrastructure issue that demands an innovative solution that eliminates the need to physically return instruments to Earth for calibration. Remote calibration, however, is a problem with no clear solution and warrants further investigation.

8.4 Maintenance and Repair Process Category

Technologies in this category are in three subcategories; electrical repairs, weld repairs, and surface repairs. The capabilities will also apply directly to or will support S&R processes. Repair capability may be needed as early as the first Altair mission. Sections 8.4.1 to 8.4.3 describe the technology candidates for the three subcategories.

8.4.1 Electronics Repair Processes

Although there is a vast array of electronic functions in space systems, there is only one primary way of mounting components, specifically, soldering. Most soldering needs can be covered by manual and automated processes.

Semiautomated electronics repair: This concept, which was developed by the CLEAR project, was derived from industrial automated workstations that can be programmed to support diagnostic probing and then perform component-level replacement using a solder reflow process. This concept may also support electronics scavenging (Ref. 27).

Advanced manual electronics repair: This technology employs special tools, fixtures, and prepackaged material kits to compensate for relatively low user-soldering skills. Such kits are currently used for circuit board rework stations. Specialized kits have been developed to “re-ball” large BGAs. Other kits provide precut adhesive stencils to improve surface-mount technology (SMT) soldering. These kits, combined with custom tools, would bridge the gap between current tools and the semiautomated reflow process (Refs. 28 and 29).

8.4.2 Welding Repair Processes

Welding has a vast array of applications in both the repair and fabrication of mechanical and structural hardware. Directed energy beam techniques are normally automated or performed robotically.

E-beam welding surface quality often eliminates postweld finishing. Ion cold welding is a metal bonding technique invented specially for high-vacuum applications.

E-beam welding: Only E-beam welding technology is viable from an environment and consumables aspect. E-beam welding can often weld materials without additional feedstock. Because of precise beam energy and steering control, welds are often very smooth. E-beam welding is not generally considered to be a manual method (Ref. 30).

E-beam precision positioning: E-beam welding has built-in beam steering capability that provides wide versatility. However, many welding applications require complex three-dimensional weld paths, and these paths require the wider range of motion that precise robotic manipulation provides. Mobile-equipment-based robots will need to be augmented with high levels of path stability to maintain the E-beam precision welding capability.

Ion cold welding: This technique is for thin-sheet or foil materials and exploits the natural tendency of ultraclean metal surfaces to bond without high temperatures. The ion-engine-derived etching technique strips oxides and contamination from the surface and allows simple mechanical pressure to bond surfaces (Ref. 31).

8.4.3 Surface Repair Processes

Often damage is limited to the hardware surface. In some cases it is superficial, but in many cases it may affect reliability. LSS hardware is expected to experience a great deal of surface damage due to operations in the lunar environment. Damage to surfaces due to wear, scratches, gouges, contamination, and erosion will affect mechanical, structural, optical, and even electrical hardware. Surface nicks, scratches, and gouges on hatch sealing surfaces or fluid flanges may produce serious leaks in critical systems. Surface damage due to shafts and bearings may ultimately lead to mechanical seizure. Replacing major hardware may not be an option when there is surface damage. The LSS operating environment has a high risk of recurring surface damage, and surface repair will be essential to keep the equipment in good condition and to prevent the loss of critical resources.

Surface repair must also address damage to surface coatings that provide protection or special surface property. Coatings can prevent corrosion, provide thermal and electrical insulation, or enhance reflectivity. Thin-film coatings may be applied to optics as anti-reflection coatings, or diamond coatings may be applied to provide scratch resistance on optical lenses or helmet faceplates. Surface coating repair technologies will need to address the removal of the damaged coating and replacement with new material. For LSS applications, the surface coating process technology must consider lunar environment compatibility.

Electrostatic and electromagnetic fields are important mechanisms for transferring and manipulating small (solid and liquid) particles that are less than 100 μm . They can be used to precisely control the placement of particles. Industry favors electrostatic methods because they allow users to eliminate many volatile chemicals and often eliminate carrier gases. Electrostatically applied coatings also reduce the problem of overspray and wasted material. Electrostatic transport methods are widely used for dry toner printing (copier and laser jet printers) and wet ink-jet applications.

In high-vacuum lunar environments, electrostatic charging is persistent, and the motion of charged particles is not impeded by aerodynamic forces. Natural electrostatic forces are believed to be responsible for levitating and mobilizing lunar dust in effects observed by Apollo astronauts. Electrostatically manipulating charged particle trajectories has been demonstrated in precision processes ranging from ink-jet printing to free-form fabrication (FFF). The recent evolution of “colloid thrusters” for precision position and attitude control for spacecraft suggests that colloidal particle beams are also possible and may be used for precise toolless finishing of fabricated hardware.

Surface and coating repair processes may involve molecular-scale matter transfer in the form of vapor and ion deposition. So-called thin-film techniques may apply film layers that are only a few molecules thick for electronics and optics applications.

Several ion-based fabrication technologies are closely related to ion engine technology, and these technologies are compatible with a high vacuum. Ion technologies involve ionized gas or ionized vaporized material that is often manipulated by both electrostatic and electromagnetic methods.

In addition, ions can be focused into precise beams that can be directed at a target. Unlike electrons, ions may be single atoms or molecular compounds that are many times more massive than electrons, and this may impart significant kinetic energy. Ion techniques can deliver material as well as extract it. A new category of ion technology called focused ion beams promises to process materials with E-beam accuracy.

Powder coating processes: Electrostatic or electromagnetic techniques can transfer solid powder by using electrostatic charges to hold the particles in place until they are fused thermally. For precise, maskless applications like copiers or laser printers, powder is conveyed via an electrostatically charged drum or belt that picks up the powder and transfers it on contact to the target surface. In space, powder can be transferred directly from the powder supply to a target without complex mechanisms or interference from aerodynamic drag, and can be projected a significant distance. Once a charged particle is in motion, the trajectory can be manipulated by electrostatic or electromagnetic means. Colloidal thrusters use charged particles as a reaction mass accelerating a particle stream to extremely high velocity. Such a device could be used to cut or shape solids much like a modern abrasive water jet. In this case, the jet is propelled by electric or magnetic fields rather than by high-pressure fluids.

Acoustic droplet coating: Coatings of nonvolatile liquids can be applied by using high-intensity ultrasound to create and project droplets without atomization gases. Once again, electrostatic fields can be used to further manipulate the droplet behaviors. These techniques can precisely place picoliter drops of material with the accuracy of the ink-jet printer (Ref. 32).

Vapor coatings: Electronics and optics make extensive use of thin-film coatings applied by vapor deposition. The two primary types are thermal and sputtering vapor deposition. Thermal vapor deposition simply vaporizes a material and condenses it onto a surface. Ion sputtering transfers molecules from a source to a substrate surface. Sputtering provides finer control and operates at much lower temperatures and can be used to apply metal, polymer, and even ceramic coatings (Refs. 33 and 34).

Ion implantation: Ion implantation is a treatment that implants material at or below the surface. This technique can change the fundamental properties of the base material. It is widely used in the creation of semiconductors. It has been used to harden tool steels as a substitute for heat treatment. Ion implantation is one way to restore properties to materials that have been altered by processes like welding. Ion implantation is a vitamin technology in that it can use a small amount of imported materials to dramatically improve the properties of bulk material (Ref. 35).

Ion etch: Ion etching has been used for both electronics and MEMS fabrication. It has been used to remove surface oxides and contaminants, allowing metals to cold weld. It also has been coupled with electron beams in electronics manufacturing (Ref. 31).

Ion milling: Focused ion beam (FIB) milling employs directed ion beams in a way similar to E-beam technology. It is a direct descendent of ion engine technology. FIB milling can drill very deep holes and precisely cut hard machine tool materials with cutting edges with unequaled sharpness. FIB is effective on ceramic and glass materials. It is unique in that the beam travels parallel, rather than perpendicular, to the surface. Thus, it acts as a shearing force against any protrusion that obstructs the beam. In producing tools, this technology has already been demonstrated as a bootstrap technology (Ref. 36).

8.5 Scavenge and Recycle Process Category

This process category includes hardware scavenging, materials scavenging, and in situ fabrication. Hardware scavenging is likely to be the earliest form of scavenging. Operations would likely employ the same tools used in maintenance, including diagnostic and test equipment. Some specialized tools may be needed for applications such as scavenging large tanks or rocket engine hardware. Propulsion systems have some intriguing potential for reuse including power generation, ISRU processing, and short-range

robotic “hopper” applications that use reaction-control thrusters. The unmanned Cargo Landers, which have a full array of avionics—including power distribution, communications, navigation, controls, and data-handling systems—will provide the best opportunities for scavengeable spares.

As hardware spare inventory is satisfied, there will be a surplus of duplicate hardware. With no specific applications, this hardware may be scavenged for its material content. Material scavenging only has value if the scavenged parts are re-formed into usable products. Special processes will be needed to convert materials into a suitable intermediate feedstock. Recycling is expected to be process and power intensive and may become significant after the Lunar Outpost is complete.

Note that most of these capabilities are currently considered to be technology gaps. In other words, there are no specific technology solutions to meet the capability. Sections 8.5.1 to 8.5.3 describe the technology candidates for the three S&R process subcategories.

8.5.1 Hardware Scavenging and Reusing Processes

Technologies in this subcategory involve removing hardware and processing at various levels of assembly down to the component level. The subcategory includes processing to make hardware suitable for spares. Reworking or reconfiguring hardware for secondary applications will involve equipment already described for repair and maintenance applications.

Electronic component scavenging: In faulty electronic assemblies, most components are still good. When surplus electronic LRUs become available, the components may be extracted as spares. Components like integrated circuits are best handled by an automatic solder reflow capability with pick-and-place component extraction. The semiautomated electronics repair apparatus described in the maintenance and repair category provides a suitable capability.

Structure element scavenging: Structural scavenging is aimed at acquiring elemental structural shapes, fasteners, and hardware for spares or new applications. Safely separating welded assemblies may require special cutting technologies. Candidates may include a lunar-oxygen-based plasma or oxygen-assisted E-beam cutting tool. Lunar regolith may serve as a working media in an electrostatic-driven, hypervelocity abrasive-particle-jet cutting tool.

8.5.2 Material Recycling Processes

Recycling requires a series of processes to decompose a material and convert it to usable feedstock. The processes needed depend on the materials selected. Metals offer the greatest versatility, but composites may make up a considerable portion of the final vehicle weight. Altair material decisions will dramatically affect recycling technologies.

Material cutting and sizing: Many materials can be reused as is but must be cut free from the parent structure and trimmed to a usable size for reapplication. Cutting processes must provide wide utility without large mechanisms or consumable cutting edges. Multipurpose E-beam, ion-beam, or plasma techniques, along with hypervelocity abrasive particle jets, may be viable.

Metal feedstock generation: This technology converts scavenged metals into feedstock for repair and fabrication. The simplest approach may be to simply melt metal (potential E-beam application) and create a metal powder feedstock by a combination of ultrasonic and electrostatic means.

Nonmetallic recycling: In addition to metals, the lander will be composed of composites, glass, ceramics, and polymers. Each has different recycling methods and levels of difficulty. The amount of a given material type available may determine if recycling is worth the development costs. At this point, the material makeup of the lander is uncertain.

8.5.3 In Situ Fabrication Processes

Processes in the in situ fabrication category pose the most challenge but will also provide the greatest payoff in achieving the supportability strategy. Without fabrication, the payoff for S&R cannot be

realized. To eliminate the need for a massive manufacturing infrastructure, NASA would need to have toolless techniques or FFF technology. The current state of the art in FFF does not produce finished parts. The technologies in the following list are intended to advance FFF to where it could produce useful products without postprocessing.

E-beam FFF processes: There are two techniques that appear to be strong candidates for lunar applications. Both employ E-beam technology and both provide a fully dense metal product. Electron beam free-form fabrication (EBF3) is derived from E-beam welding, and electron beam melting (EBM) is derived from early powder-sintering technologies. EBF3 has been tested in zero-gravity aircraft flights and has a higher TRL. EBM appears to outperform EBF3 by producing products that more closely represent the final product. EBF3, however, has greater control of the feedstock, has much greater multiaxis mobility, and has demonstrated its ability to perform postprocessing. EBF3 has demonstrated low sensitivity to gravity and, thus, is more robust (Ref. 37).

Preencapsulation: This technique minimizes or eliminates the need for postprocessing by using premachined parts that are embedded into the product. By encapsulating a precision feature, the fabrication process can form the bulk material around the prepositioned part without distorting it. Similar techniques have been used for casting and conventional welding. The approach is consistent with the vitamin-technology aspect of the supportability strategy because it exploits a small amount of high-value, encapsulated hardware along with bulk scavenged materials.

Progressive refinement FFF: Most FFF techniques employ an open-loop approach to build products in a series of two-dimensional planes. Variations in material feedstock delivery or fusion with the underlying form create irregularities. Without refining or correcting the accumulated flaws, the resulting product is equivalent to a rough cast part requiring postprocess machining. The elimination of postprocess machining, and its resource and compatibility issues, is essential to achieving the supportability strategy. The progressive refinement approach provides constant monitoring of the true shape and combines additive and subtractive techniques that provide closed-loop control and that correct accumulating deviations. Progressively changing the scale to smaller additive and subtractive increments down to the molecular scale will make it possible to produce highly accurate products. This capability may involve a hybridization of E-beam technology and the material-deposition technologies used in surface repair, including extractive ion etching and milling technologies. Ion implantation could further enhance the end product by altering the final surface properties to make the product harder and more durable.

8.6 Preliminary Process Technology Evaluation

Table V shows a preliminary characterization of the technology candidates in terms of technology infusion. This can be considered to be an initial screening based on the parameters described in Section 6.0. In the mass, power, and crew time columns, the technology may have no impact; it may have a low, medium, or high impact, or it may reduce the mass, power, or crew time.

The evaluation considers the technology's role in risk reduction and the overall utility the technology provides. Process technologies are often payloads, and unlike embedded technologies, the mass may impact only a single mission. In contrast, the anticipated increase or reduction of crew time is a key measure of the operational impact of the technology.

TABLE V.—PROCESS TECHNOLOGY PRELIMINARY CHARACTERISTICS

Technology	TRL ^a	Mass	Power	Crew time	Risk reduction	Utility
Diagnostics signature analysis	4	Low	Low	Reduced	Enables minimal-training crew diagnostics	Electronic diagnostics
Synthetic instruments	3	Low	Low	Reduced	Diagnoses in situ faults and tests repairs	Electronic diagnostics
Conductor diagnostics	3	Low	Low	Reduced	Diagnoses wire and connector faults	Electronic diagnostics
Optical measurement	3	Low	Low	Reduced	Inspects hardware with optical diagnostics	Simplified diagnostics
X-ray imaging	4	Moderate	Moderate	Moderate	Detects hidden faults	Simplified diagnostics
E-beam imaging	3	Moderate	Moderate	Moderate	Inspects weld repairs	Precise flaw detection
Diagnostic assistant	4	Low	Low	Reduced	Reduces crew diagnostic errors	Prognostics and diagnostics
Remote calibration	2	Moderate	Low	Reduced	Reduces risk of damage to hardware	Precise in situ tools
Advanced manual electronics repair	4	Moderate	Moderate	Low	Repairs electronics in situ	Component-level electronics repair
Semiautomatic electronics repair	3	Moderate	Moderate	Moderate	Reduces dependency on crew skills	Component-level electronics repair
E-beam welding	5 to 6	High	High	Moderate	Repairs metal structures in situ	Repair of structures
Ion cold welding	4	Moderate	High	Moderate	Repairs metal sheet and foils in situ	Processing of thin stock
Powder deposition	3	Moderate	Moderate	Moderate	Repairs thick-film coatings in situ	Surface repair and fabrication
Liquid droplet	3	Moderate	Moderate	Moderate	Repairs coatings in situ without masks	Surface repair and fabrication
Vapor and sputter films	3	Low to moderate	Moderate	Moderate	Repairs thin-film electronics and optics	Surface repair and fabrication
Ion implantation	4	Moderate	Moderate	Low	Restores hardware subsurface properties	Surface repair and fabrication
Ion etch and milling	3	Moderate	High	Low	Restores precision surfaces	Surface repair and fabrication
Electronic component scavenging	3	Moderate	Moderate	Moderate	Recovers electronic components for spares	Repair and fabrication
Structure element scavenging	2	Moderate	High	High	Recovers structural hardware for repairs	Repair and fabrication
E-beam fabrication	5	High	High	Moderate	Fabricates replacement parts	Repair and fabrication
Preencapsulation	2 to 3	Moderate	High	Moderate	Simplifies in situ part fabrication	Repair and fabrication
FFF ^b successive refinement	2	High	High	Moderate	Precisely finishes components in situ	Repair and fabrication
Metal feedstock generation	2	High	High	Moderate	Converts scavenged metals for fabrication	Repair and fabrication
Nonmetallic recycling	2	High	High	Moderate	Recycles nonmetallic materials	Repair and fabrication

^aTechnology Readiness Level.

^bFree-form fabrication.

8.7 Process Technology Development Schedules

The schedule for supportability process technology is more complex than that for embedded technology, and it involves an incremental phased development. Certain technologies are driven by early needs, whereas others are driven by the available infrastructure required to support them. All technologies are expected to achieve TRL 6 well before Altair’s first flight. Further refinement of the schedule will require the project formulation process, which is scheduled to follow the delivery of this technology roadmap.

8.7.1 Phased Technology Development Milestone Rationale

Plans call for the supportability roadmap to be followed by the supportability technology development formulation process in fiscal year 2010. Process technologies are external to flight hardware. They are not expected to be on the flight vehicle development path, and they are more consistent with an independent payload schedule. Process technologies are aimed at providing specific capabilities, and development is driven by end applications. Although the focus has been on LSS, the first user is expected to be Altair and certain capabilities will be tailored for Altair. These process technologies will follow the Altair schedule, and there are roughly 10 years available from now to the first landings of Altair. This timeframe may also accommodate technology demonstrations onboard the ISS. Other capabilities will be developed on schedules consistent with the buildup and completion of the Lunar Outpost.

Rather than show a development schedule for individual technologies, the Supportability Project has grouped the process technologies into three development paths based on the point where the capability is needed. The three capability milestones are Altair First Crewed Flight, Delivery of Habitat 1 (Lunar Outpost), and Outpost Complete.

8.7.2 Supportability Capabilities for Altair First Crewed Flight Milestone: 2021

The supportability capabilities needed by the Altair First Crewed Flight milestone follow:

- Basic DTV and M&R capabilities will be provided to the first crewed mission.
- Capabilities will be limited to contingency tools because of vehicle space and weight constraints and the expendable nature of the vehicle. This group will include handheld diagnostic tools and manual repair tools.
- Technology development should achieve TRL 6 at least 4 years before the Altair Flight Readiness Review (FRR) to allow adequate time for it to be fully developed as flight equipment and to support Altair vehicle integration.

8.7.3 Supportability Capabilities for Delivery of Habitat 1 (Outpost) Milestone: 2025

The supportability capabilities needed by the Delivery of Habitat 1 milestone follow:

- Most DTV and M&R capabilities will be delivered and hardware scavenging capability will be phased in following the Delivery of Habitat 1.
- Capabilities will be scaled to suit the permanent nature of the habitat and the ability to accommodate DTV and M&R equipment in a workstation. Phasing will be affected by the availability of LSS infrastructure and accommodations of the Lunar Outpost. Thus delivery will span the time between Delivery of Habitat 1 (Lunar Outpost) and Outpost Complete.
- Hardware scavenging capabilities will be provided to allow the crew to exploit lander hardware for spares.
- Hardware scavenging capabilities phasing depends on the buildup of the outpost infrastructure and on how aggressively the program exploits lander hardware.
- Technology development should achieve TRL 6 at 2 years before the Altair FRR.

8.7.4 Supportability Capabilities for Outpost Complete Milestone: 2027

The supportability capabilities needed by the Outpost Complete milestone follow:

- All DTV and M&R capabilities will be in place.
- Hardware scavenging technology will be operational, and scavenging for spares will have begun.
- Materials S&R and in situ fabrication will have been phased in.
- Material S&R capabilities will be energy intensive, so the Lunar Outpost will have to have an adequate power infrastructure.
- Accumulation of an inventory of landers will be needed to make materials scavenging feasible.
- Technology development will need to achieve TRL 6 prior to the Altair FRR.

8.8 Technology Decision Gates

The decision gate where the first process down-selection occurs is directly linked with the embedded down-selection point prior to Altair System Design Review. The TRL-6 milestones shown in Figure 4 are where technology infusion occurs.

8.9 Development Cost Considerations

Of the capabilities listed, many involve a distinct process technology that is new and enabling for lunar applications. The majority of the processes already exist in industry but may be rarely used because of specialized high-vacuum requirements that are very expensive to build and maintain and that tend to impede flexibility. The high investment and operating cost must be amortized over many units; thus, these processes rarely appear outside the high-production-rate or high-value facilities of the electronics and aerospace industry. In contrast, the high-vacuum lunar environment is ideal, and these technologies now appear as low-mass, power-efficient, and comparatively low-cost alternatives to converting a conventional process.

9.0 Supportability Technology Incremental Development Schedule

Embedded technologies impose some added development risk in the host hardware and must be integrated into the flight hardware development schedule. Because the primary vehicle of interest is the Altair Lunar Lander, the schedules for all embedded technologies are virtually locked in step with the vehicle schedule. There is limited overlap or competition between the embedded technologies. A selected embedded technology, however, may reduce the need for a process technology. In some cases, process technologies depend on embedded technologies. Because embedded technology selections are expected to impact the selection of process technologies, embedded technologies are a priority in the overall development schedule.

Process technologies are external to flight hardware. They are not expected to be on the Altair vehicle development critical path and are more consistent with an independent payload schedule. The schedule for process technologies will be more complex and driven by the needs of early lunar sortie missions and the buildup of the Lunar Outpost infrastructure. As a result, embedded and process technology development was broken into four increments as shown in Figure 4.

9.1 Technology Formulation and Decision Gates

Supportability roadmap completion will be followed by the supportability technology development formulation process. This formulation will include the details of technology phasing and will establish decision gates. Technology down-selection will occur at the decision gates that are linked with the Altair development milestones. The TRL-6 milestones shown in Figure 4 are where technology infusion will occur. Because embedded technologies will be integrated into the flight hardware, they will have to reach TRL 6 by Altair PDR.

In many cases the embedded and process technologies are complementary, and the down-selection point for process technologies will be affected by the infusion of the embedded technologies. If an embedded technology is dropped, the related process technology may be expanded. Conversely, successful infusion of embedded technology may result in descoping or dropping a process technology.

The embedded technology schedule is intended to provide 3 years beyond the TRL-6 infusion point to ensure full operational readiness 2 years before flight. In contrast, equipment payload process technologies are driven by sortie and outpost mission schedules and are independent of the vehicle development. The schedule also shows that a number of process technologies will begin in a low-intensity feasibility phase and then be launched as individual development projects on 2-year centers. Altogether, four technology development increments are shown in Figure 4.

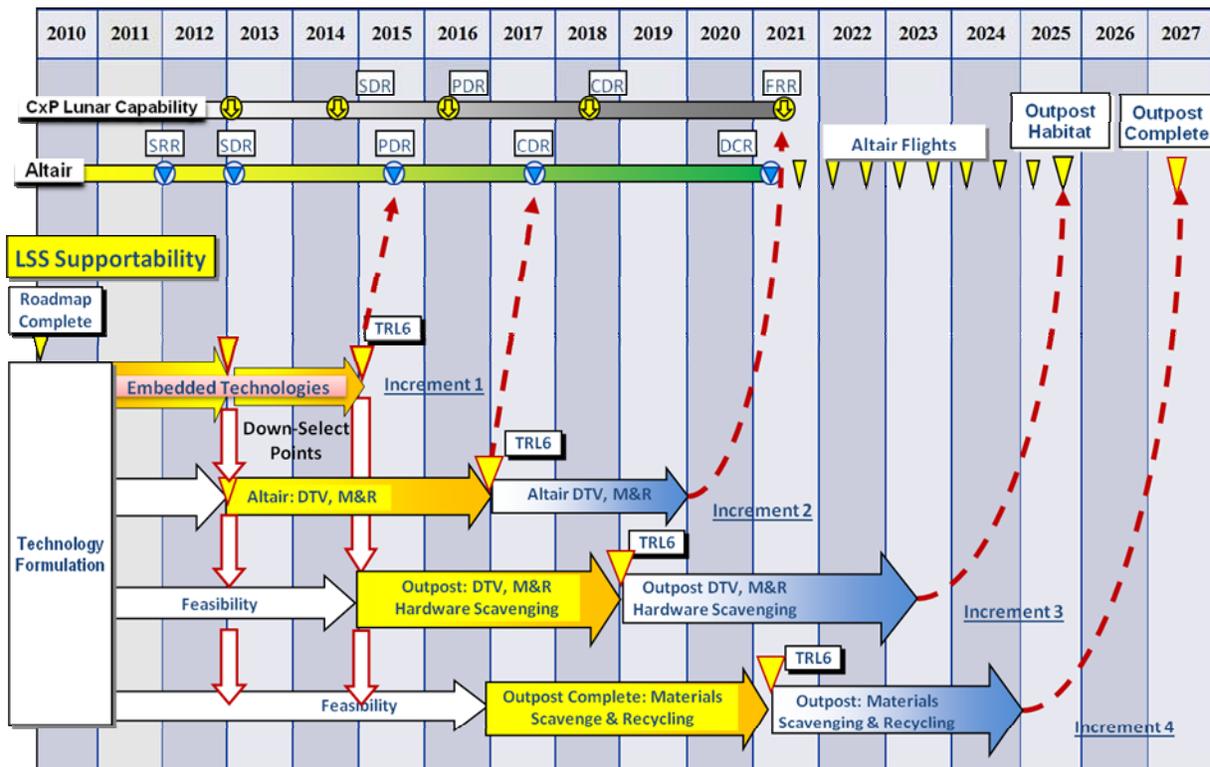


Figure 4.—Supportability technologies incremental development schedule. CxP, Constellation Program; SDR, System Design Review; PDR, Preliminary Design Review; CDR, Critical Design Review; FRR, Flight Readiness Review; TRL, Technology Readiness Level; SRR, System Requirements Review; DCR, Design Concept Review; LSS, Lunar Surface Systems; DTV, diagnostics, test, and verification; M&R, maintenance and repair.

9.2 Increment 1

Currently all embedded technologies are intended for Altair First Crewed Flight (2021). Embedded technology of TRL 6 and infusion by Altair and should be achieved by Altair PDR (2015). The embedded technologies are aimed at providing multiple supportability capabilities without increasing the size, weight, and power of the flight hardware while decreasing crew time required for DTV, M&R, and S&R operations. For practical reasons, not all of the technologies will be applied to Altair. Most technologies are expected to apply directly to LSS. Scavenging however, will drive the need to ensure that Altair has compatibility, commonality, access, and internal features that support reusability.

9.3 Increment 2

For process technologies, a limited set of DTV and M&R tools will be available for Altair First Crewed Flight. The TRL-6 infusion point is set to support the Altair Critical Design Review (CDR, 2017). Altair, as an expendable spacecraft, has limited need and accommodations for spares or repair capabilities. For crew safety, a basic set of readily available tools and diagnostics equipment will be needed. The diagnostic and test equipment may be as limited as a single portable SI.

9.4 Increment 3

For Delivery of Habitat 1 to the Lunar Outpost (2025), a set of DTV, M&R, and hardware scavenging equipment will be available 2 years before flight. The TRL-6 infusion point is at launch minus 6 years (2019). The actual delivery of complete DTV and M&R capabilities will likely be spread over several flights during the buildup of the Lunar Outpost. With the accumulation of spent landers, hardware scavenging may begin to create an inventory of spares at various levels of assembly.

9.5 Increment 4

For Outpost Complete (2027), the material S&R technologies will be delivered 2 years before flight. The TRL-6 infusion point will be at launch minus 6 years (2021). By the time of Outpost Complete, scavenging of Altair hardware may likely exceed the expected spares needed. The surplus hardware can be scavenged for its material content. Eventually, the capability to convert the materials to feedstock will be needed as a resource for extended repair and component fabrication.

10.0 Concluding Remarks

In preparing this document, the project was provided information by various subject matter experts and contributors representing NASA centers, NASA contractors, the U.S. Navy, the U.S. Air Force, and industry. Supportability strategies have been discussed from Apollo through the space shuttles, the Russian Mir, and the International Space Station (ISS). Lessons learned have been provided by the U.S. Navy, ISS Flight Operations, the NASA Shuttle Logistics Depot, and the NASA Spacecraft Services Depot. Lunar Surface Systems (LSS) needs were established from various sources, including the Surface Architecture Reference Document (SARD), Component-Level Electronic-Assembly Repair (CLEAR) project documents, and needs derived from lessons learned. The LSS Supportability Implementation Plan for missions beyond Earth orbit was provided by the LSS Supportability Project.

In the LSS Supportability Implementation Plan and the LSS supportability technology development strategy, the goal of achieving a high degree of resource independence was established as the focus for defining the criteria and selecting the technologies. From this goal and the lessons learned submitted by contributors, two types of technologies were established. Specifically, embedded and process technologies were defined on the basis of the method of technology infusion. Both types have three primary application categories: diagnostics, test, and verification (DTV), maintenance and repair (M&R), and scavenge and recycle (S&R).

Embedded and process technologies are distinctly different in how they are infused into the program, and thus each has different development cycles. Embedded technologies are directly linked to the Altair development milestones, whereas process technologies are linked to their end application and have more schedule latitude. Embedded technology by the Exploration Technology Development Program (ETDP) will end when the technology is infused into components or is adopted by the Altair program. Embedded technologies must be at Technology Readiness Level (TRL) 6 by the time of the Altair Preliminary Design Review (PDR). Embedded technology leads process technology development on the overall schedule and may have a direct impact on the selection and development of process technologies. Therefore, embedded technology down-selection milestones are linked to the process technology down-selection milestones. Finally, the technology development has been organized into four waves, or increments.

The supportability technology roadmap has identified a wider set of capabilities and technologies beyond M&R. In many ways, this effort is the first exposure of the underlying complexity involved in establishing a human presence on another world. It is likely that only a portion of these technologies will prove viable. In some areas, only a capability is defined, which may represent a gap in the current technology base. Some near-term capabilities will exploit technologies developed by other programs. Some downstream capabilities that are envisioned, such as S&R, will require a long-term development

commitment, but they may ultimately provide the greatest return on investment by providing a bootstrap capability. Overall, these capabilities will provide suitable capabilities for Mars while helping to minimize the operational costs of lunar exploration. This LSS Supportability Technology Development Roadmap is a living document that is expected to evolve. This document is expected to help shape the operational infrastructure of human exploration.

Appendix A.—Simple Calculation of Relative Payload Mass Fraction

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The calculation of how much payload a launch vehicle can deliver to any particular location in space or orbit is complex, but it can be simplified by using a simple mass fraction analysis based on appropriate past vehicle performance. For calculating the payload delivered to a near Earth orbit compared with landing the payload on the Moon, the Apollo Saturn V rocket is appropriate.

- Saturn V vehicle delivered 118 000 kg to low Earth orbit (LEO)
- Saturn V vehicle delivered 47 000 kg to lunar orbit

The Apollo landing was complicated by the fact that the command module and lander modules separated in lunar orbit. The Constellation Program approach is even more complicated because Altair and *Orion* are launched on separate vehicles, rendezvous in LEO, transfer from Earth to lunar orbit on the Earth-departure stage, and then separate in lunar orbit.

For simplicity, it is assumed that a single Cargo Lander of 47 000 kg descends from lunar orbit. The mass fraction indicates the vehicle mass after each propulsive maneuver divided by the initial mass:

lunar deorbit mass fraction = 0.994 (Ref. 3), where $0.994(47\ 000) = 46\ 718$

lunar descent and landing mass fraction = 0.552, where $0.552(46\ 718) = 25\ 788$

Thus,

comparative payload mass fraction = $25\ 788\text{-kg landing mass} / 118\ 000\text{-kg LEO mass} \sim 0.22$

This implies that any vehicle will deliver to the lunar surface only 22 percent of the mass it could deliver to the International Space Station.

Appendix B.—International Space Station Flight Operations Tools and Equipment

Data provided by
NASA Johnson Space Center’s Mechanisms and Maintenance Group
NASA Johnson Space Center’s Logistics and Maintenance Group

Table VI to Table VIII represent equipment capability recommendations based on the experience of International Space Station flight operations. Table VI addresses the needed capabilities and the corresponding tools required to support orbital-replacement-unit-level maintenance.

TABLE VI.—INTERNATIONAL SPACE STATION (ISS) ORBITAL REPLACEMENT UNIT (ORU)
AND BASIC MAINTENANCE EQUIPMENT

ISS maintenance capability	Tools needed for ISS capability
Tighten and loosen fasteners and hardware	Combination wrenches, sockets, hex-head wrenches, crowfoot wrenches, ratchets, extensions, and special drivers for certain fasteners
Torque fasteners and hardware; check accuracy	Torque wrenches (to cover the complete torque range) and analyzers to check accuracy
Measure (coarse to very fine)	Tape measure, calipers, and feeler gauges
Provide visual or physical access to confined spaces	Inspection mirror, mechanical fingers, and fiberscope with extraction tools
Cut material (wire and harnesses, thin metal, hoses, cloth, etc.)	Wire cutters, cable cutters, scissors, hack saw, bone saw, tin snips, and knives
Drive fasteners (large number or large torque)	Power tool (drill, driver, and batteries)
Charge batteries	Battery charger (28 Vdc) and 3.0-A-hr nickel-metal hydride (NiMH) batteries
Build and modify connector jumpers, bypass, copper wiring, etc.	Wire of varying sizes; pins and sockets to match; tools to crimp pins and sockets; ring, spade, and tongue terminals of varying sizes; and other repair tools
Fabricate jumpers and bypasses (22, 20, 16, and 12 gauge)	Wire, pins and sockets, terminals, and tools (wire cutter and pin, socket, and terminal crimper)
Repair wire harnesses (22, 20, 16, and 12 gauge)	Wire splices, splice tool, pin and socket removal tools, pin, socket, and terminal crimper
Bypass wire harnesses (0, 4, and 8 gauge)	Premade jumpers, bus connectors, and step-down jumpers (0 to 4, 4 to 8, and 8 to 12)
Measure voltage, resistance, continuity, etc.	Voltmeter and ohmmeter
Measure complex signals (waveforms, etc.)	Oscilloscope
Measure temperature	Voltmeter and temperature probe
Measure pressure	Voltmeter and pressure probe
Measure current	Voltmeter and current probe
Clean foreign contamination from connectors	Compressed gas cylinders (nitrogen) and nozzles
Tape items (various applications)	Tape of various kinds (duct, kapton, electrical, metal, foam, double-stick, etc.)
Hold and grip hardware during maintenance or other activities	Vice, clamps, work table, and vice-grip pliers
Contain dust, debris, and materials during maintenance activities	Containment system and vacuum
Provide supplemental lighting to support maintenance tasks	Battery-powered flashlights and light-emitting diode (LED) lights, plug-in ISS-powered lights, and headband lights
Clean up debris, provide filter cleaning, etc.	Vacuum cleaner
View confined spaces, including via remote video	Fiberscope, light source, and camera
Provide personal protective equipment (for crew)	Goggles, gloves, masks, hearing protection, and garments
Cleanup and dispose of toxic and hazardous material	Bags, wipes, and vacuum
Solder and desolder	Soldering iron, batteries, solder, solder tools, and foreign object damage (FOD) and fume control
Hold and grip small components during maintenance or other activities	Tweezers (various types)

Table VII addresses the capabilities and tools needed for intermediate level (shop replaceable unit (SRU)) maintenance involving component replacement particularly for contingency situations. Table VIII indicates the tools that could be eliminated by embedding features in the original design that make hardware easier to access and service.

TABLE VII.—INTERNATIONAL SPACE STATION (ISS) I-LEVEL, COMPONENT LEVEL, AND CONTINGENCY MAINTENANCE

ISS maintenance capability	Tools needed for ISS capability
File metal (to smooth or modify)	Files of varying types
Tap and die (to clean and repair threads or cut new threads)	Taps and dies of varying sizes, holders, and foreign debris control
Drill holes	Drill, batteries, drill bits of varying sizes, and center punch
Repair and diagnose Ethernet cables	Tool for crimping new connector, diagnostics for cable (continuity, crosstalk, and fault)
Diagnose copper cables	Copper cable tester (time-domain reflectometer) and software
Diagnose and clean fiber optics	Fiber light source, fiber meter, and fiber-cleaning hardware
Measure airflow	Air-velocity meter
Measure noise	Audio meter
Record diagnostic measurements results (from meters)	Meter and associated probes; oscilloscope
Diagnose low-voltage sources (<5 Vdc)	Low-voltage logic analyzer and software
Diagnose the powering of hardware (0 to 150 Vdc)	Diagnostic power supply (variable output)
Diagnose data buses (1553)	Pass-1000 and software
Diagnose Multiplexer/Demultiplexer Module (MDM)	MDM on-orbit tester, software, and MDM interface hardware
Pull and insert circuit cards from and into computers (MDMs)	MDM card puller
Repair sewn components or, in contingency, stitch parts together	Sewing thread, needles, and pliers or device to push and pull thread through heavy material
Fabricate lightweight metal structures (ducting, support structures, etc.)	Aluminum sheet, snips, hand punch, pop rivets, rivet gun, and wire
Fabricate from nonmetallic parts, storing spare material	Teflon sheet or other plastic; scissors
Store spare bolts, nuts, and/or washers	Bolts, nuts, and washers
Extract broken screws and fasteners	Screw extractors, drill bits, drill, and batteries
Detect and repair leaks in a pressurized volume (air leaks)	Ultrasonic leak detector, repair materials, and repair tools
Repair leaks in pressurized fluid lines (coolant)	Capability to clamp over damaged line or splice
Lubricate parts and materials	Lubrication and applicator
Sharpen cutting tools	Hone (diamond)
Magnify vision to see small parts, small labels, etc.	Magnifying glasses and wearable magnifying visor

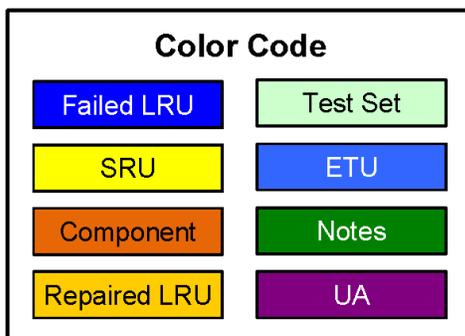
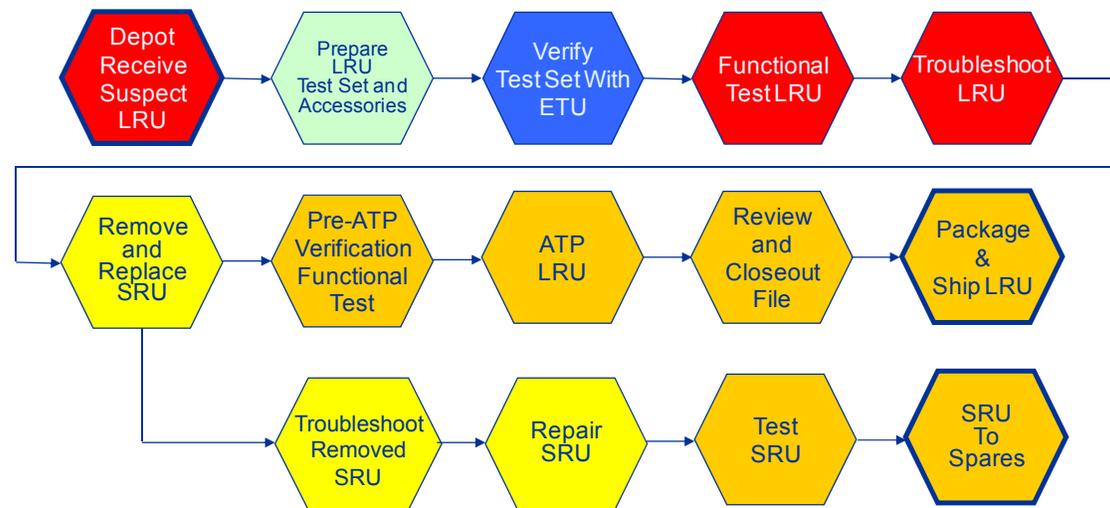
TABLE VIII.—INTERNATIONAL SPACE STATION (ISS) TOOLS ELIMINATED BY PROPER EMBEDDED SUPPORTABILITY

ISS maintenance capability	Tools needed for ISS capability
Measure running torque	Dial torque wrench
Remove stuck fasteners or remove components	Hammer, chisel, pry bar, and breaker bar
Remove and replace external MDM Cotherm	Scraper tool, new Cotherm, and vacuum cleaner
Repair and replace helicoil inserts	Assorted inserts, insert tools, and tang breakoff tools
Fill, drain, circulate, and purge pressurized fluid lines	Fluid reservoir, pump, valve system, and hoses
Tighten and loosen special Gamah fittings (high-pressure)	Tool to tighten while holding reaction, tools to replace metal seal, and replacement seals
Sample and monitor cooling fluid (pH sample, ammonia (NH ₃), and ortho-phthalaldehyde (OPA), and return sample)	Sampling valve, NH ₃ and OPA sample bags, and pH test strips
Provide portable ventilation	Portable battery-powered or plug-in fan

Appendix C.—NASA Shuttle Logistics Depot Avionics Laboratory Hands-On Repair Process

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The following process flow diagrams (Figure 5) describe the processes involved in the maintenance of a space shuttle line replaceable unit (LRU). Lunar Surface Systems (LSS) supportability technologies will need to reduce, eliminate, or consolidate as many of the steps as possible. A closely coordinated ground support staff could relieve the crew of many steps.



ATP acceptance test procedure
 CDR Critical Design Review
 CM configuration management
 ETU engineering test unit
 FMEA failure modes and effects analysis
 FTA fault tree analysis
 IDMM intermediate and depot maintenance manual
 KT linear Increasing failure rate (math variable)
 LRU line replaceable unit
 NSLD NASA Shuttle Logistics Depot
 OEM original equipment manufacturer
 PC&S production control and scheduling
 PDR Preliminary Design Review
 PRR parts rework replacement
 PRT prevention resolution team
 QE quality engineering
 RC root cause
 RE reliability engineering
 SRU shop replaceable unit
 TT&E test teardown and evaluate
 UA unexplained anomaly

Figure 5.—Ideal repair flow chart.

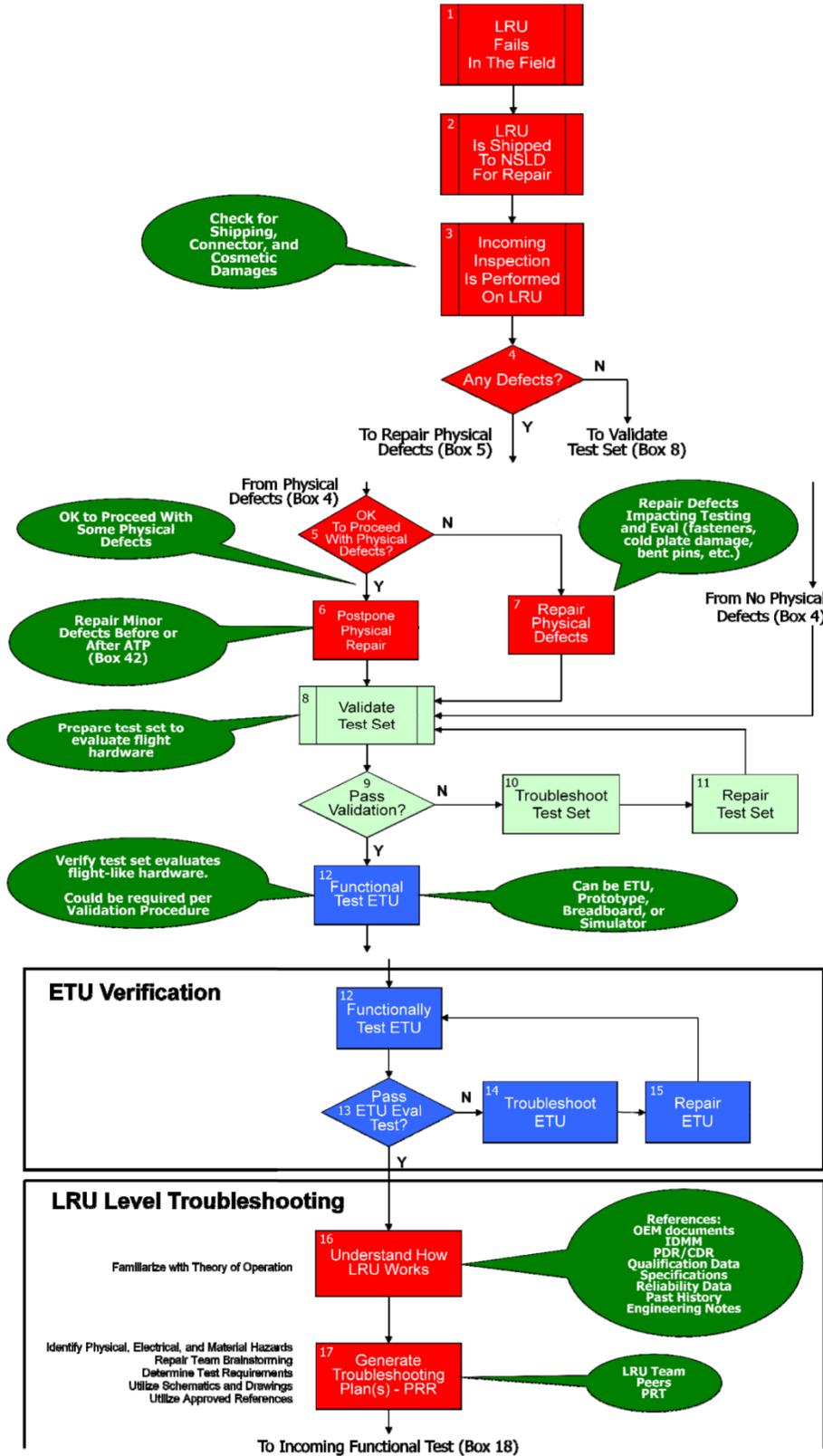
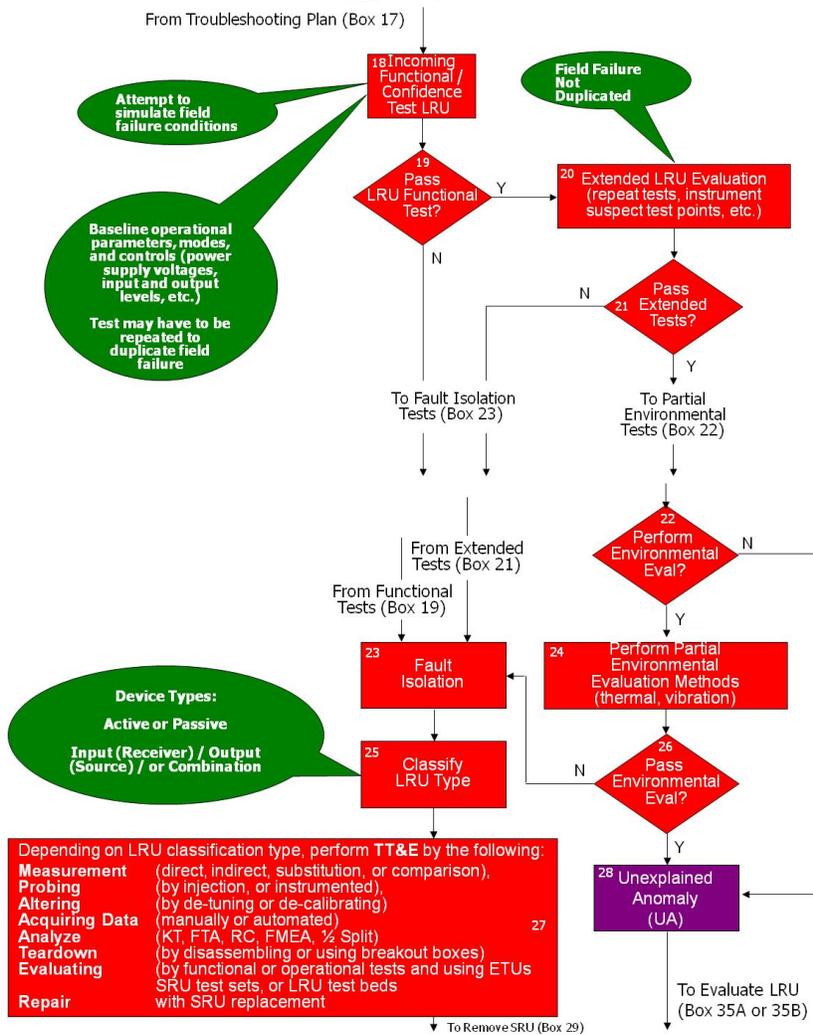


Figure 5.—Continued.

LRU Level Troubleshooting (continued)



SRU Removal and Replacement

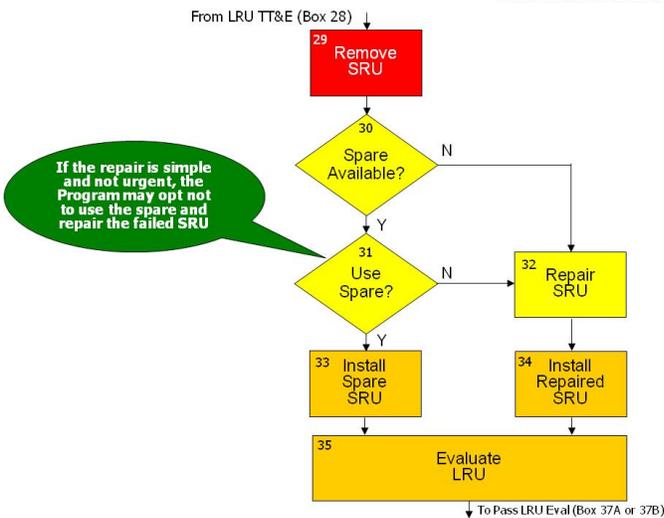


Figure 5.—Continued.

LRU Level Troubleshooting (concluded)

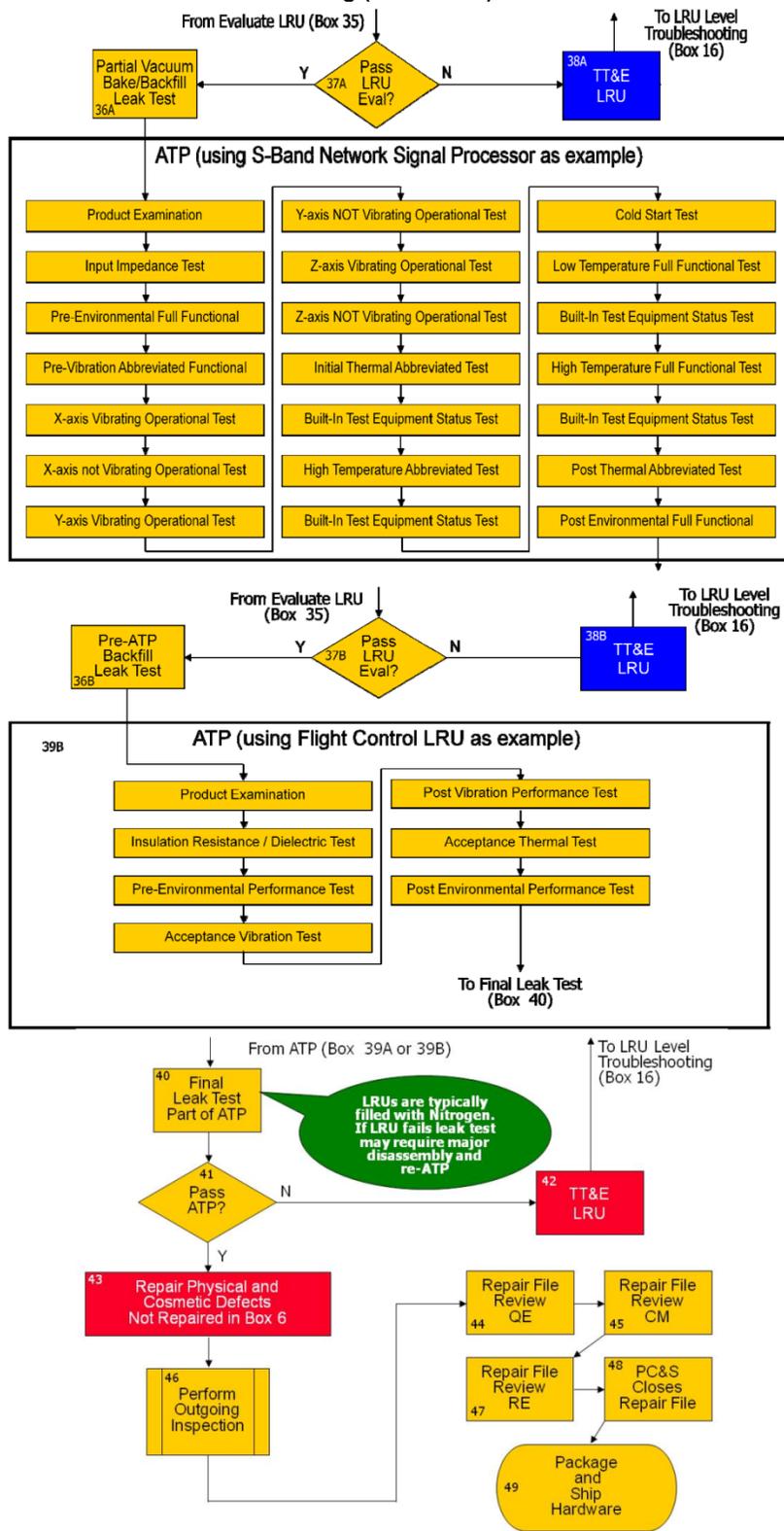


Figure 5.—Continued.

SRU Level Troubleshooting

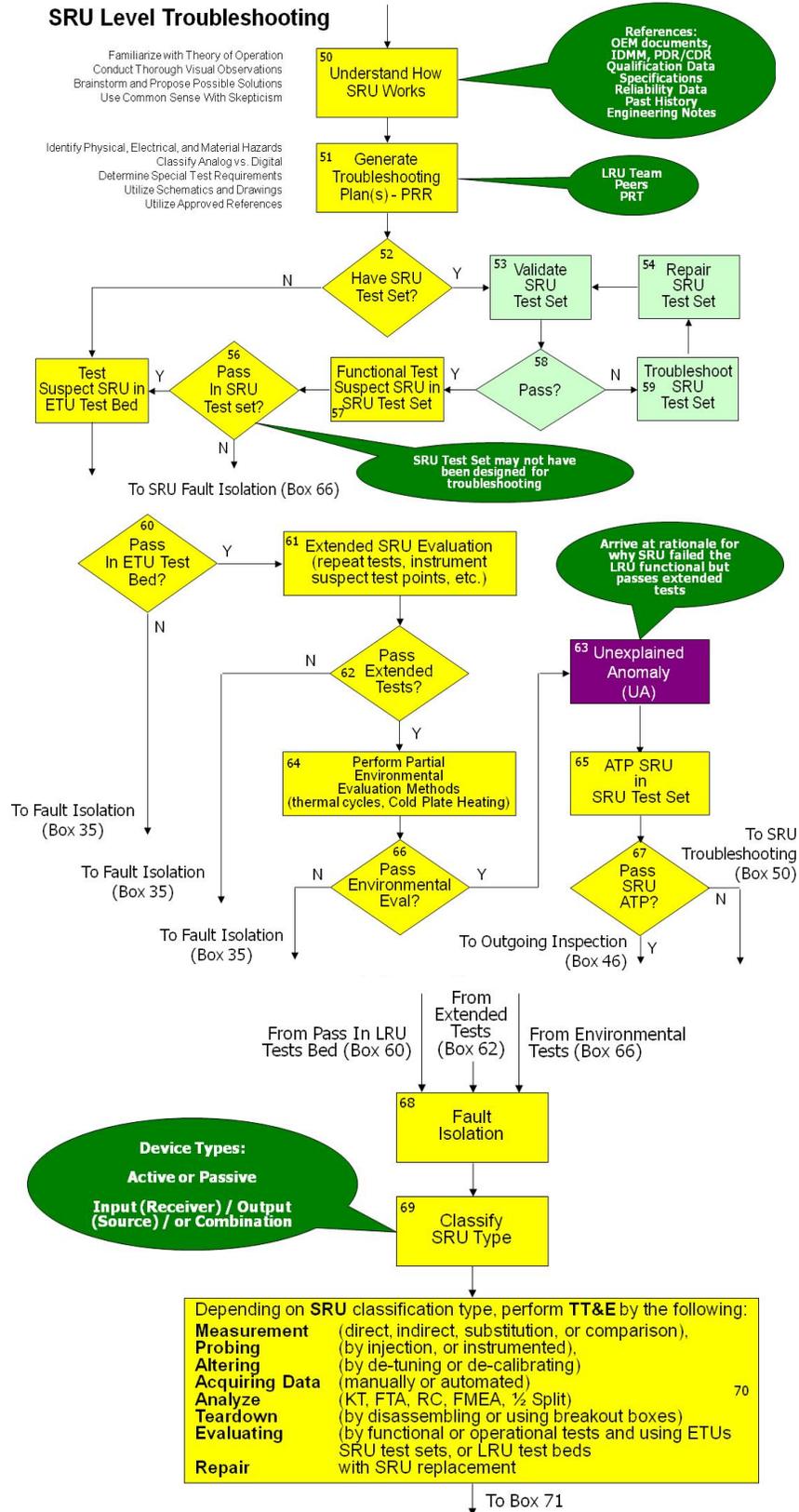


Figure 5.—Continued.

SRU Level Troubleshooting (concluded)

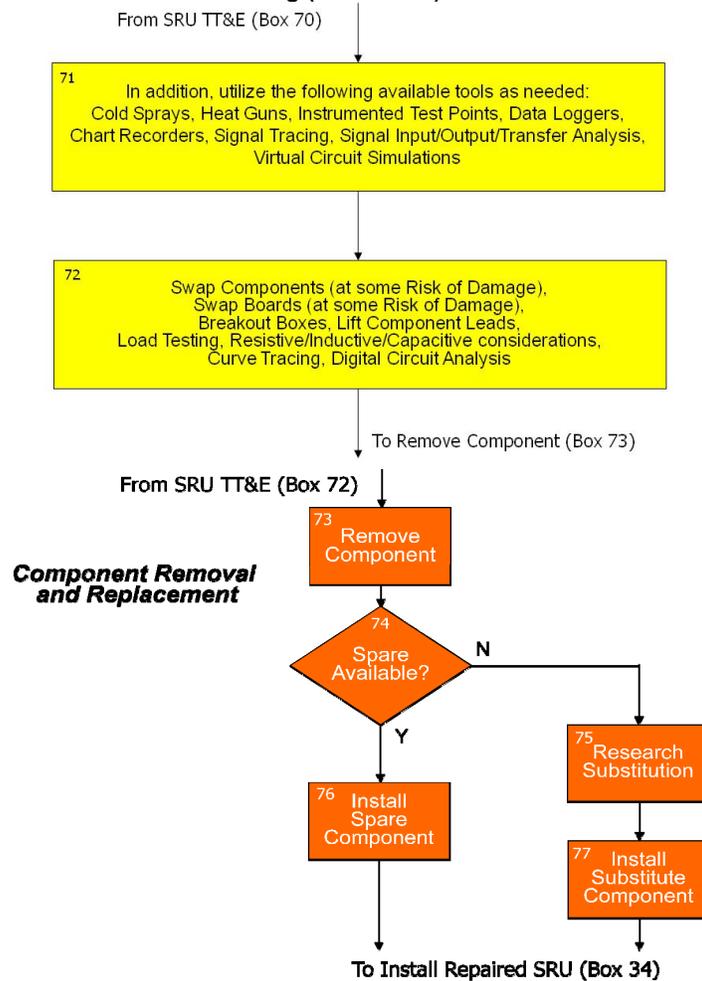


Figure 5.—Concluded.

Appendix D.—Supportability Beyond Earth Orbit

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D.1 Constellation Program Architecture

The Constellation Program architecture is a combination of vehicles, facilities, design reference missions (DRMs), and mission phases, as shown in Figure 6.

The lunar DRMs include the Lunar Sortie Crew DRM and the Lunar Outpost DRM, which include the uncrewed Cargo Altair DRM, the Visiting Lunar Outpost Expedition DRM, the Resident Lunar Outpost Expedition DRM, and the Outpost Remote Operations DRM. The supportability concept for the Lunar Sortie Crew DRM emphasizes the use of redundancy and high-reliability components that require limited maintenance over the typical 7-day mission. The Altair sortie mission carries a maintenance toolkit, which will be based on the *Orion* toolkit.

As currently envisioned, the Lunar Outpost mission sequence begins with an uncrewed test flight of the outpost Crew Altair in 2019 and then the Human Lunar Return sortie mission to the outpost site at the lunar south pole by 2020. After that, there are two crew missions and one to two cargo missions per year to the lunar surface. NASA is currently evaluating a wide range of alternative mission concepts and is working with international partners to converge on global point-of-departure architecture by mid-2010.

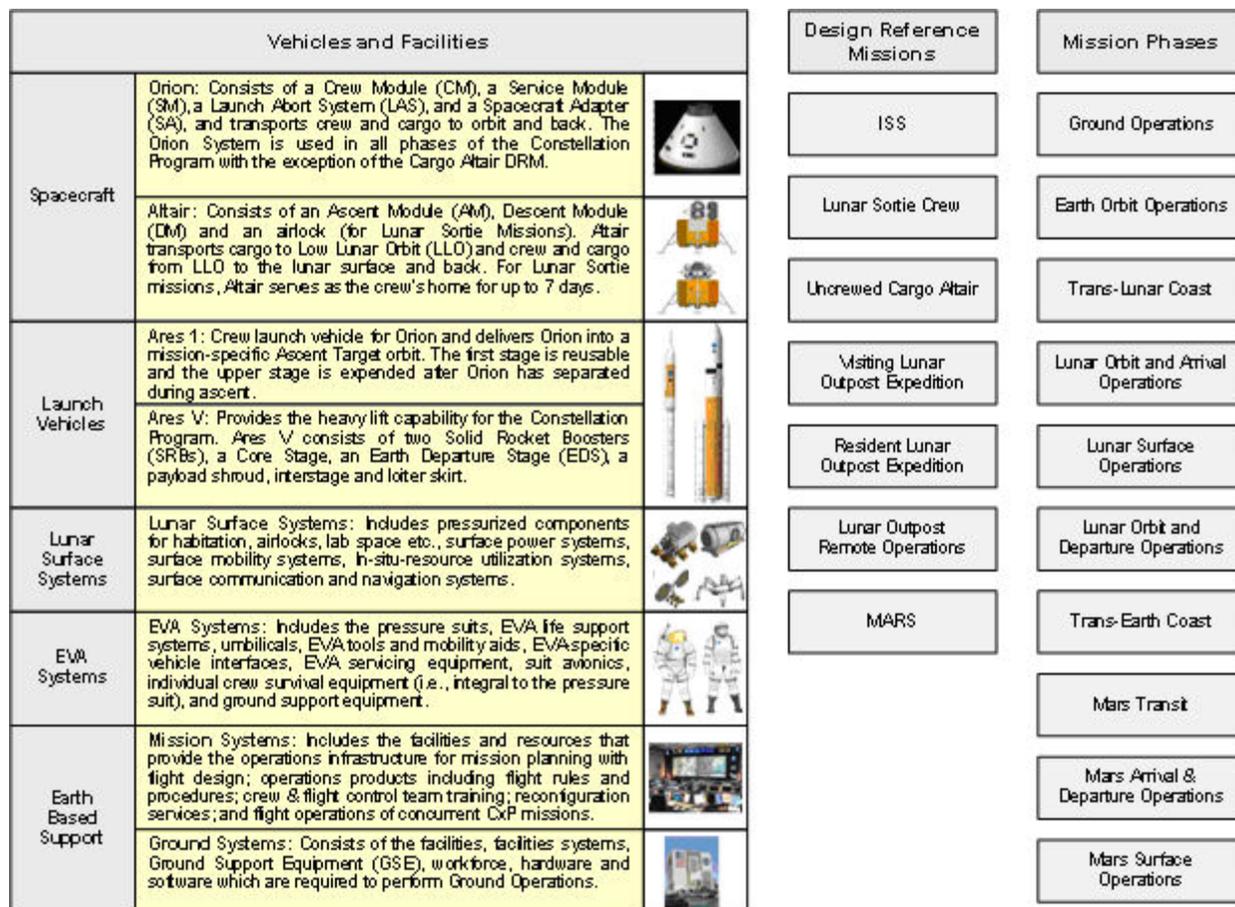


Figure 6.—Lunar design reference missions. ISS, International Space Station; EVA, extravehicular activity; CxP, Constellation Program.

During the outpost missions, the airlock functionality is already provided on the surface and, therefore, the outpost Crew Altair does not have the same attached airlock as for the sortie version, as shown in Figure 7(a). In both configurations, however, the current plan is to leave the Altair Descent Module (DM) on the lunar surface near the outpost and to guide the Altair Ascent Module (AM) toward a destructive impact on the lunar surface after the crew has transferred to the *Orion* in low lunar orbit. However, NASA is considering several lander reusability options to reduce the buildup of spent landers on the surface.

As currently envisioned, there are no major Lunar Surface Systems (LSS) elements delivered on the outpost Crew Altair flights; however, a limited amount of science or logistics cargo may be delivered. As the designs of the Altair and *Orion* evolve, there may become a need to develop a contingency maintenance capability for the Altair AM and the orbiting *Orion* capsule as part of the overall LSS Supportability Implementation Plan. This capability might include the storage of critical Altair AM and *Orion* spares at the outpost and both preventative and corrective maintenance (CM) of the Altair AM by the outpost crew. There may also be an option to scavenge parts from the Altair DM for use as outpost spares or primary structure.

The outpost Cargo Altair, as shown in Figure 8, will deliver the LSS elements to the lunar surface. The elements will be integrated onto the Altair at the NASA Kennedy Space Center and the Ground Operations Project will provide all prelaunch services and maintenance for LSS elements prior to launch on the Ares V.

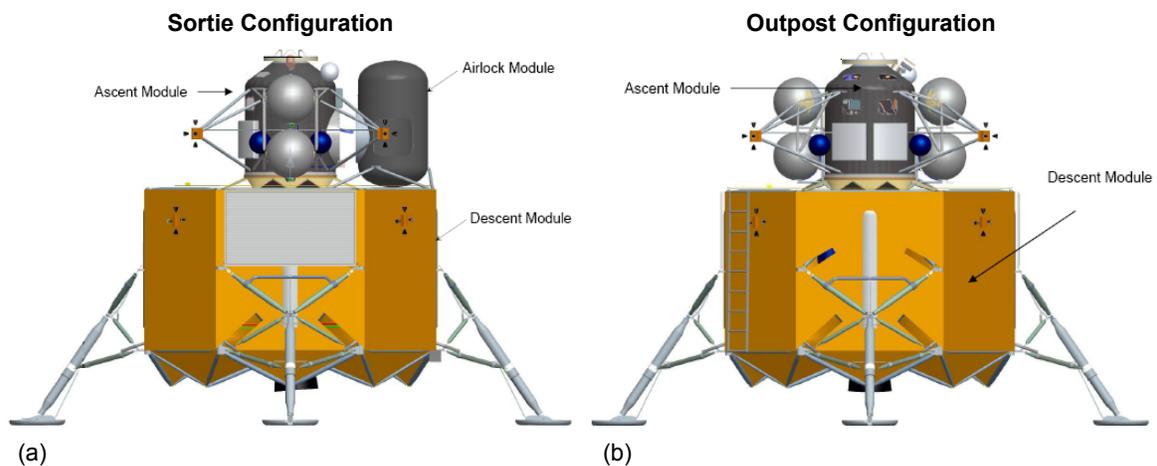


Figure 7.—Altair in sortie and outpost configurations.



Figure 8.—Cargo Lander and Outpost Lander configuration.

While in transit, the LSS elements will be partially powered for checkout, health monitoring, and thermal control. After landing, the LSS elements will remain on the Cargo Altair until the crew and/or heavy lift offloading systems arrive. The landing zone, as shown in Figure 9, will be separated from the permanent outpost in the habitation zone by no more than 1 km.

The LSS used in the outpost mission phases will be composed of numerous concepts for habitats, mobility assets, power and communications infrastructure, and facilities for in situ resource utilization. The LSS Project Office is still evaluating different scenarios, and the LSS elements are still very conceptual. Some of the current concepts are shown in Table IX.

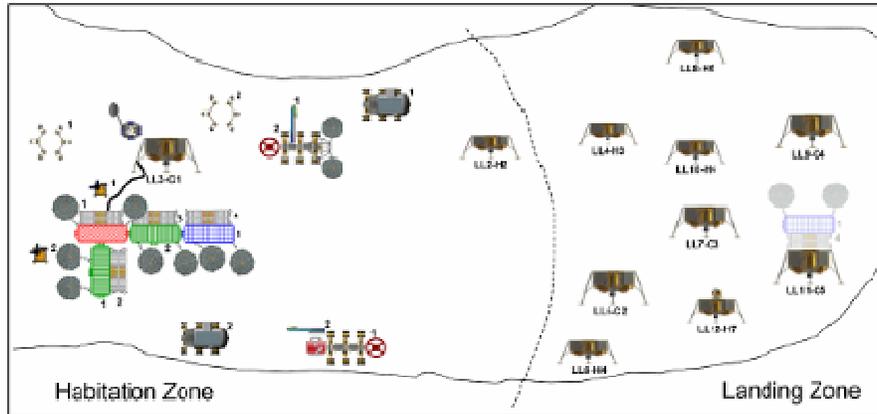


Figure 9.—Lunar Outpost. LL, Lunar Lander.

TABLE IX.—LUNAR SURFACE SYSTEM ELEMENTS

Element	Description
	The Core Habitat will contain the core outpost habitation subsystems, a four-crewmember airlock/suitlock, a spacesuit maintenance area, dust control, a geosciences lab, and stowage. The Reusable Pressurized Logistics Modules (RPLM 1 and 2) will be similar in design to the Core Habitat but will lack many of the core Environmental Control and Life Support System (ECLSS) subsystems. The Disposable Pressurized Logistics Modules (DPLMs) will use a common pressure shell but are only intended for short-term occupancy. Inflatable habitat options are also being considered.
	The Chariot Mobility Chassis (CMC) is a roving vehicle designed to carry up to four crewmembers (two nominally) in an unpressurized environment or in a pressurized cab. The chassis will be able to support up to 3000 kg at nominal speeds and greater payloads at reduced speeds. It will have interfaces to connect tools for outpost support operation. The chassis will be controllable directly through the chassis driving kit or the pressurized crew cab, telerobotically, or autonomously.
	The Lunar Electric Rover (LER) is a pressurized crew cabin that will sit on top of the CMC. It will be designed to mate to the pressurized habitation elements (or to another LER) to allow pressurized crew transfer for short- and medium-duration roving missions. The spacesuit ports on the LER will allow easy access to the lunar surface and allow astronauts to transfer from the LER to the extravehicular activity (EVA) suits with a low overhead in crew time.
	The (Tri-ATHLETE) (Three-legged All-Terrain Hex-Legged Extraterrestrial Explorer) has three limbs and wheels on a chevron-shaped frame, such that two Tri-ATHLETES will be able to dock on opposite sides of a power and support unit (PSU). This arrangement eliminates the need for individual ATHLETE limbs to be attached by EVA astronauts to a PSU, or the need for a PSU to be able to slide on rails off an Altair onto a dedicated ATHLETE vehicle
	The Lunar Communication Terminal (LCT) will provide local communications around its location via a wide area network as well as Earth communications via a relay or direct to Earth using S-band and K-band links. Navigation services will be provided over the S band.

TABLE IX.—LUNAR SURFACE SYSTEM ELEMENTS

Element	Description
	The Robotic Assistant (RA) will be available to conduct fine dexterous manipulation. It will be mountable on Chassis A, Chassis C, and/or ATHLETE. It then will become a complete end-to-end system. NASA is currently evaluating ways in which to use the RA to perform maintenance, both in conjunction with the surface crew and independently when the crew is not present.
	The In Situ Resource Utilization (ISRU) O₂ Plant will produce 500 kg of molecular oxygen (O ₂) per year, and is intended to be sent as early as possible to demonstrate feasibility before the start of 180-day crew stays. This plant is designed to fit on the CMC for delivery, and could either remain on the CMC or be offloaded to a permanent location on the lunar surface.
	The Mobile Power Unit (MPU) is a set of solar arrays and additional batteries that will be combined with a CMC to provide a mobile power source for the architecture. The solar arrays will be the same as the ones integrated with the habitation elements carried by the PSU (two 5.5-m-diameter <i>Orion</i> -class arrays).

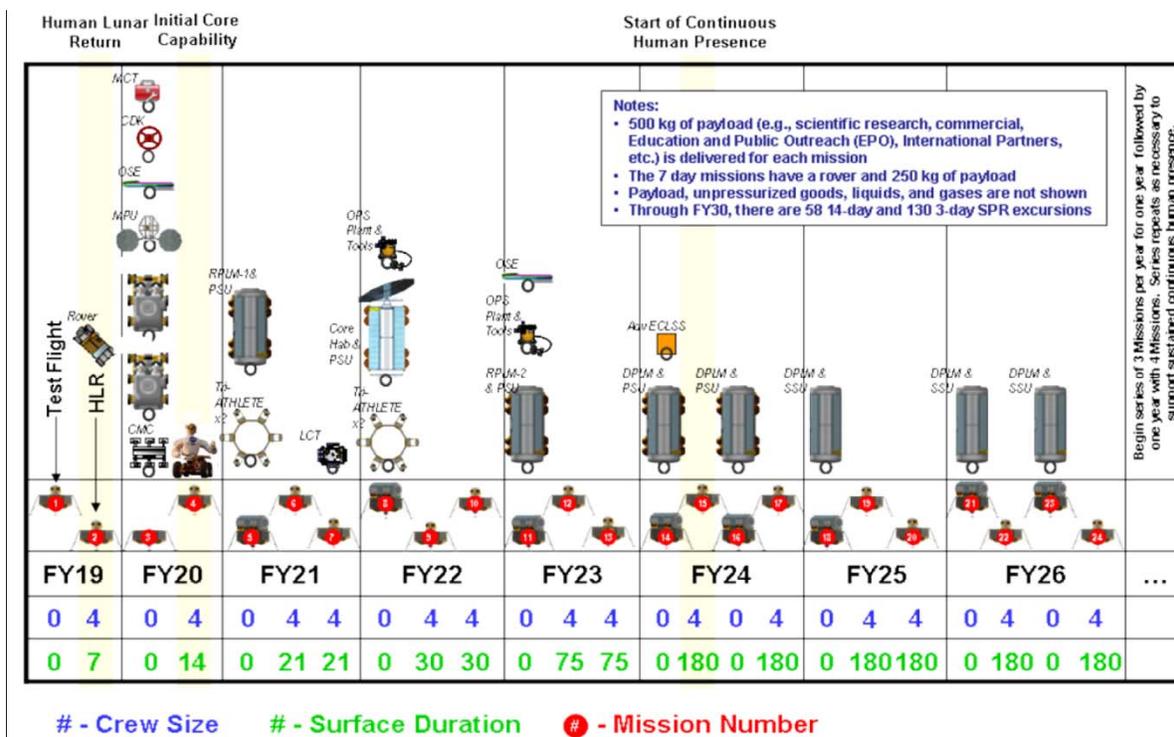


Figure 10.—Outpost build sequence. MCT, mobile communications terminal; CDK, chassis driving kit ; OSE, outpost support equipment; MPU, Mobile Power Unit; OPS, operations; SPR, Small Pressurized Rover; LER, Lunar Electric Rover; RPLM, Reusable Pressurized Logistics Module; PSU, power and support unit; Cor Hab, Core Habitat; AdvECLSS, Advanced Environmental Control and Life Support System; HLR, Human Lunar Return; CMC, Chariot Mobility Chassis; RA, Robotic Assistant; Tri-ATHLETE, Three-legged All-Terrain Hex-Legged Extraterrestrial Explorer; LCT, Lunar Communication Terminal; DPLM, Disposable Pressurized Logistics Module; SSU, Structural Support Unit; FY, fiscal year.

Over the course of approximately 5 years beginning in 2019–2020, the Lunar Outpost will be constructed using a combination of crew and cargo missions. The LSS elements will be delivered using Altair Cargo Landers, and the crewed missions will increase in length depending on the availability of logistics cargo, such as food, water, and clothing. LSS is still defining the buildup sequence and which elements will be part of the final configuration. NASA is working with international partners and other entities to define International Point of Departure architecture by mid-2010. The buildup sequence in Figure 10 is representative of a possible outpost configuration.

From a supportability standpoint, the key point from Figure 10 is that the availability of outpost resources such as power, data, communications, launch mass allocation, crew time, and stowage volume increases over time. The supportability concept must evolve within these constrained resources, and any technology development effort must strive to reduce resource consumption whenever possible.

D.2 Supportability of Lunar Design Reference Missions

The LSS supportability concept, as shown in Figure 11, is separated into two main operations phases. The first is Nominal Operations, where the maintenance approach is structured to maximize the functional availability of the LSSs while reducing the overall supportability burden in terms of logistics mass, volume, crew time for maintenance, and cost. The activities during Nominal Operations will follow a predetermined process and schedule that will be managed by the Constellation Program Mission Operations project. The second area is Contingency Operations, which will occur when, despite the best efforts to anticipate failures through preventative and predictive maintenance (PM and PdM) techniques, a random failure occurs that may or may not threaten the life of the crew. During Contingency Operations, the maintenance will be reactive, in that the crew will be reacting to an actual hardware failure. The safety of the crew will take the highest priority, and restoring the LSS elements to a functional state in the shortest time possible will also be a driver. The elements within each of these operational phases are discussed in Sections D.3 and D.4.

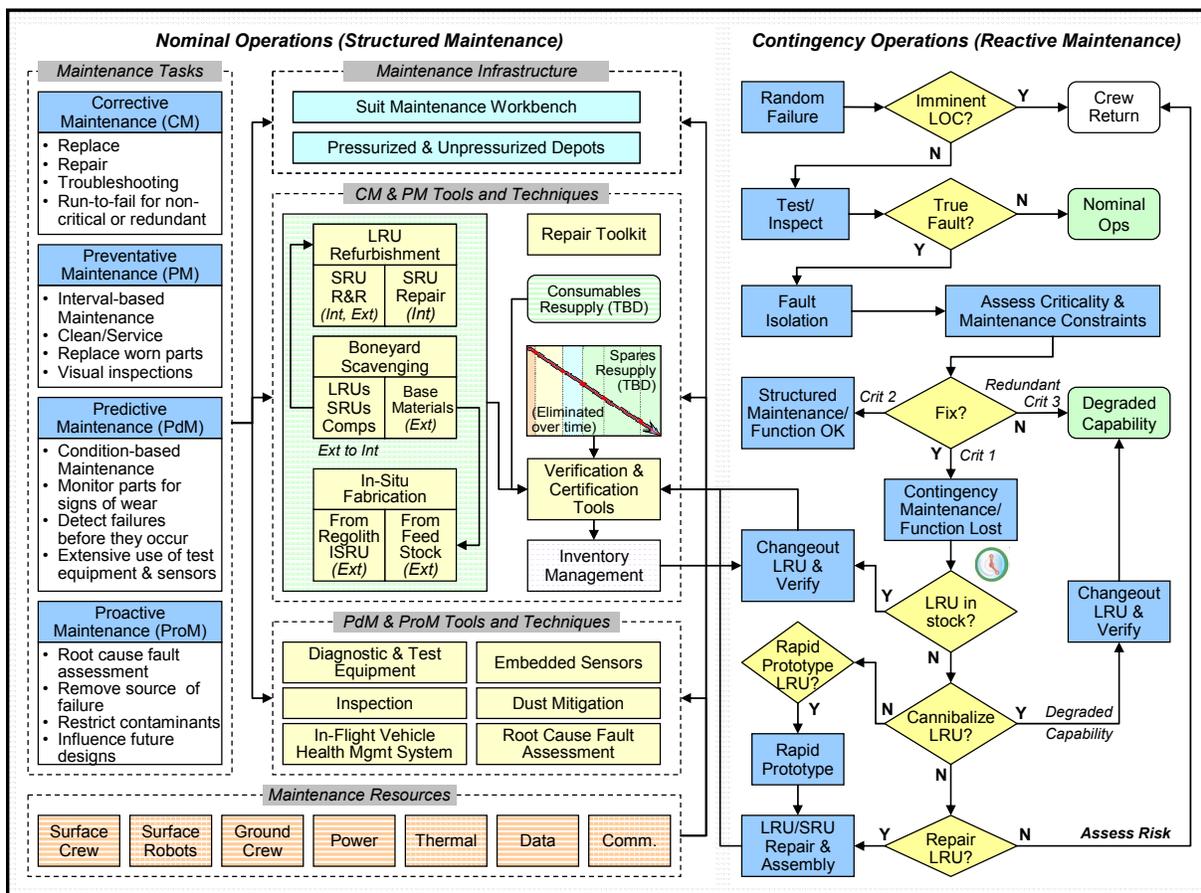


Figure 11.—Maintenance and repair operations concept. LOC, loss of crew (top right); LRU, line replaceable unit; SRU, shop replaceable unit; R&R, remove and replace; Int, internal; Ext, external; TBD, to be determined; Comps, components; Crit, criticality level; ISRU, in situ resource utilization; Comm, communications.

D.3 Nominal Operations (Structured Maintenance) Concept

During the Nominal Operations phase, maintenance operations will be performed on a continuous basis by the ground crew, surface crew, and surface robotic assets. Even without a surface crew present, maintenance operations could continue in an autonomous state, especially in PdM and proactive maintenance (ProM), where continuous monitoring of the status of LSS hardware is important, especially prior to crew arrival. As shown in Figure 11, there will be five emphasis areas within the Nominal Operations phase: maintenance types, maintenance infrastructure, CM and PM tools and techniques, PdM and ProM tools and techniques, and maintenance resources.

Four primary maintenance types are used in the LSS Supportability Implementation Plan: CM, PM, PdM, and ProM. CM includes all the activities to replace or repair a hardware item after a failure has occurred. It also includes troubleshooting to verify and isolate the failure and some amount of diagnostics and test to verify that it is fully functional. PM will focus on interval-based maintenance (e.g., 90-day servicing or preemptively replacing a worn part with a 730-day life limit at 700 days), cleaning and servicing, and inspections by the surface crew. PdM will focus on condition-based maintenance, where systems and components will be monitored continuously to determine if there are any signs of degraded performance. When the hardware reaches a condition level at which it was predetermined that maintenance would be necessary, it is scheduled to minimize system downtime.

For LSS, PdM will focus on the use of autonomous technologies and embedded sensors to minimize crew time. ProM will identify the root cause of failure in the hardware so that a maintenance plan can be designed to eliminate or reduce those causes (e.g., restrict the dust contamination that leads to the filter failure that brings down the carbon dioxide removal system. In this example, PdM would focus on monitoring the status of the filter and scheduling a change out after the dust particulate count exceeds a certain threshold value.

The maintenance infrastructure area describes the physical locations where maintenance will be performed on the lunar surface. In the early outpost configurations, the maintenance location may be a simple workbench in one of the pressurized modules, such as the Core Habitat. The initial workbench will likely have multiple functions and may be deployed only when maintenance is required. During the initial phase, both storage volume and maintenance resources will be strictly limited, and many of the maintenance techniques will have to be delayed until the outpost can provide more dedicated volume, power, data, and communications bandwidth.

After the outpost buildup is complete, dedicated pressurized and unpressurized maintenance facilities will be completed. It is anticipated that these facilities will be constructed from spent logistics modules, scavenged structural supports, and other discarded items in order to limit additional launch mass. For the pressurized maintenance depot, a pressurized logistics module will be retrofitted with Environmental Control and Life Support System (ECLSS) hardware and other accommodations that will allow it to support the maintenance crew for whatever period of time is necessary. For the unpressurized depot, a hangar-type structure will be constructed using scavenged parts and will protect unpressurized spares and maintenance equipment from radiation and thermal cycling.

The CM and PM tools and techniques category covers a wide range of processes, technologies, and equipment. One of the key attributes of the LSS Supportability Implementation Plan is the focus on intermediate and depot-level maintenance. On the International Space Station (ISS), maintenance is only performed at the organizational level, where larger subsystem assemblies are removed and replaced at the LRU level if a failure occurs. For LSS, the emphasis is on LRU refurbishment, which includes both shop-replaceable-unit- (SRU-) level remove and replace (R&R) and SRU repair.

A repair toolkit and a sparing and consumables resupply will be needed for CM. The sparing philosophy for LSS will change over time. In the early years, a higher degree of sparing will be provided to allow for R&R of LRUs and SRUs before refurbishment technologies come on line. Over the course of outpost development, spares and maintenance mass will be reduced to the greatest extent possible without having an adverse effect on crew safety or system downtime.

In addition to refurbishing LRUs, LSS intends to reuse as much of the hardware delivered to the lunar surface as possible. After the initial buildup, three to four landers per year will arrive in the landing zone, consisting of two Altair Crew Landers and one to two Altair Cargo Landers. The descent module (DM) from these landers and the logistics carriers from the cargo flights could be scavenged for LRUs, SRUs, and components, as well as for base materials for in situ fabrication. The extravehicular activity (EVA) portable life-support system components could also be scavenged since they will be left on the surface at the end of each crew expedition. The ability to scavenge parts will depend on the lander configuration, the ease of disassembly, the condition of the parts and materials after long-term exposure to the lunar environment, and the availability of crew time and other outpost resources to perform the scavenging.

In the area of in situ fabrication, several technologies are being considered. Regardless of the exact technology, the availability and quality of feedstock is an important issue. It is likely that the in situ fabrication capability will evolve over time. At first, feedstock may be delivered as part of the logistics cargo, and demonstrations will be performed to validate the performance of the technologies and the quality of structural and structural-mechanical components that are made. Over time, more reliance will be placed on the fabrication capability, and the use of lunar regolith and scavenged materials as a source of feedstock will be examined fully.

In addition to the CM and PM tools and techniques already outlined, several other functions will be performed by the lunar maintenance depot. One of the most important areas will be the test, verification, and certification of repaired, refurbished, scavenged, and fabricated hardware. Historically within NASA, this process can take months, if not years, and it is unclear at this point in time how the process will be adapted to accommodate surface-based verification, where the crew time and timeline will be strictly limited. The degree to which testing and diagnostics could be automated and/or controlled from the ground will have a big impact on the overall success of the LSS supportability concept.

Another of the areas under the Nominal Operations phase is PdM and ProM tools and techniques. Most of the technologies discussed in this roadmap will fall into this category. In addition to the diagnostic and test equipment already discussed, there will be a wide range of inspection tools, in-flight vehicle health management technologies, embedded sensors, dust-mitigation techniques, and tools for root-cause fault analysis (RCFA). The RCFA technologies will be particularly important to LSS because, unlike in other NASA programs, there will be no capability to return failed hardware to Earth to determine the cause of the failure. The ability to perform RCFA in situ will be very important—especially if failures due to common causes become a major factor.

The final area under the Nominal Operations phase is maintenance resources. This area will include the surface assets that will be allocated as a resource as well as surface and ground crew time, surface robot time (which may also consume ground or surface crew time if the robots are teleoperated), and distributed systems such as power, thermal control, data, and communications. Surface crew time will be one of the most critical resources for supportability since crew maintenance time will compete directly with crew science and exploration time. Therefore, crew maintenance time will have to be reduced as much as possible. However, since many of the supportability technologies will also consume large quantities of power and require significant monitoring by the ground (leading to high data and communications bandwidth demand), these other resources will also need to be considered. The availability of both surface crew time and distributed system resources will increase as the outpost matures; therefore, the scope of the supportability function will likely increase at the same rate as resources availability.

D.4 Contingency Operations (Reactive Maintenance) Concept

Despite the best attempts to predict and prevent random failures from occurring during the Nominal Operations phase, there will always be a risk that an unanticipated event could bring down one or more of the LSSs. Some possible events include the failure of redundant systems because of a common cause failure, human error, radiation events, failure of adjacent systems due to unrelated failures, power surges, and the failure of the monitors and sensors that allow system degradation to go undetected until it is too late to perform PM.

The first step after the Contingency Operations phase is initiated will be to determine if there is an imminent danger to the surface crew. If there is, it may be necessary to evacuate the crew and abort the mission. If it is determined that there is no imminent threat, the surface and ground crews will first determine whether there is a true fault, and if so, they will attempt to isolate it to the subsystem, LRU, SRU, or even component level. Here, the criticality of the hardware will determine how long the crew has to perform tests and inspections. After the fault is isolated, a determination will be made by ground control about whether the item should be fixed, and once again, this will depend on the criticality of the item. If the failure is in the communications system, it is possible that the surface crew may lose contact with the ground, and emergency procedures will be written far in advance to plan for this potential case.

If the item is of low criticality, it is possible that the ground and surface crew will just go back into Nominal Operations and finish the mission in a degraded capability mode. If the item is mission critical (Crit 2) but not life threatening, the repair could be handled through the normal depot maintenance procedures. If the item is life critical, but not imminently so (i.e., the failure removes a level of fault tolerance for a critical function), the ground and surface may decide to take the system offline and fix the part in real time. In this situation, the “clock is ticking” on system downtime, and the sequence in which maintenance procedures are considered would likely be based on how much time each requires. The number of possible procedures will also vary over the course of the outpost lifetime since different capabilities will be ramped up over time.

In order to implement the LSS supportability concept, NASA will require a plan for significantly reducing the spares and maintenance cargo resupply from Earth. Section D.5 outlines the phased reductions in spares mass and the steps, analyses, and investments required to make them possible.

D.5 Lunar Surface Systems Supportability Implementation Plan

The goal of the LSS Supportability Implementation Plan, as illustrated in Figure 12, is to significantly reduce the spares and maintenance cargo mass requirement over the course of the Lunar Outpost lifetime without forcing a proportional increase in the consumption of other resources, such as crew time, power, and data and communications bandwidth. Because all of these resources are intricately linked, the main emphasis of pre-System Requirements Review (SRR) analysis and tradeoffs will be to determine the relationships between them and how to best optimize the overall supportability approach to achieve the best balance between them.

The approach depicted in Figure 12 shows an evolutionary path that begins with the current ISS Support Program and culminates in the 500-day Mars Mission. Currently, the ISS Support Program focuses on LRU-level R&R procedures that are designed to minimize the amount of crew time required for maintenance. In the ISS plan, failed LRUs are replaced on-orbit and then returned on the space shuttle and refurbished and reflown later. This approach represents the current state of the art for long-term support of crewed bases.

The ISS approach is considered to be the starting point of the LSS strategy to reduce spares and limit other resources, and ISS historical performance serves as a key analog for spares and maintenance requirements. The LSS approach represented in Figure 12 shows the steps necessary to reduce these requirements. The approach is separated into phases including the initial ISS Support phase using the space shuttles as the primary resupply vehicles (ending in 2010); the ISS Support phase beginning with international vehicle support only and then introducing *Orion* and commercial orbital transportation system vehicles as they come on line (2010 to 2016+); initial lunar orbital flights and Altair sortie missions to the Moon (Human Lunar Return in 2020); Lunar Outpost phase (beginning in 2020 and separated into the three subphases of Construction, Permanent Human Presence, and Mars-Forward); and finally the Mars Mission phase beginning around 2030. In each of these phases, steps will be necessary to ensure that the end goal of a self-sufficient outpost capability is met.

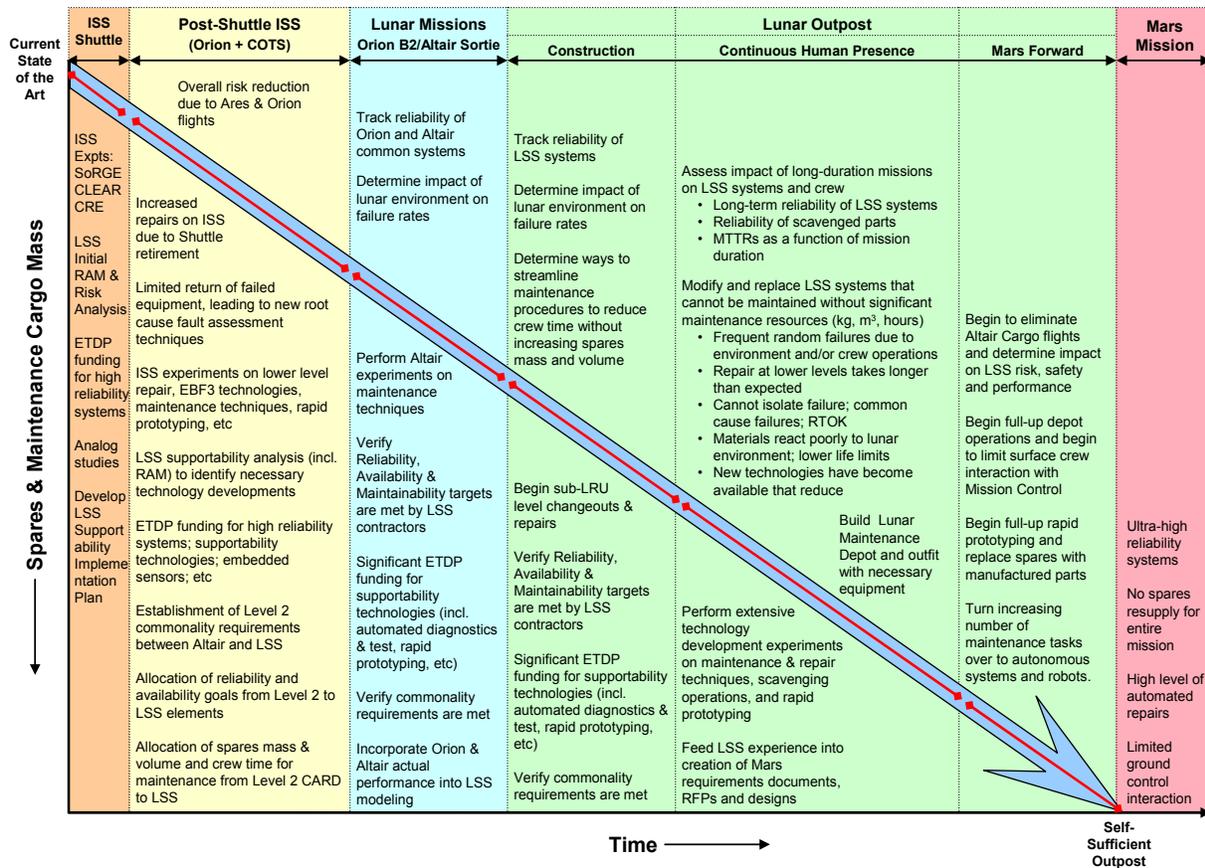


Figure 12.—Lunar Surface Systems (LSS) Supportability Implementation Plan. ISS, International Space Station; COTS, commercial orbital transportation system; SoRGE, Soldering in Reduced Gravity Experiment; CLEAR, Component-Level Electronic-Assembly Repair; CRE, Component Repair Experiment; MTTR, mean time to repair; RAM, reliability, availability, and maintainability; ETDP, Exploration Technology Development Program; EBF3, electron beam free-form fabrication; RTOK, Retest OK; LRU, line replaceable unit; CARD, Constellation Architecture Requirements Document; RFP, request for proposal.

NASA is currently in the first phase of this evolutionary path. In this phase, the initial LSS supportability concept will be defined, and analog studies will be conducted to identify the drivers for maintenance on the ISS and to incorporate best practices for supportability from other NASA programs, Department of Defense programs, and industrial applications. In this phase, some ISS experiments in lower levels of repair will be conducted (e.g., Soldering in Reduced Gravity (SoRGE), Component-Level Electronic-Assembly Repair (CLEAR), and the Component Repair Experiment (CRE)) and initial reliability, availability, and maintainability (RAM) analysis will be performed using conceptual LSS system and element designs. The Exploration Technology Development Program's (ETDP's) Supportability Project is also defining the technology development roadmap. The end of the first phase corresponds to the space shuttle retirement in 2010, and the LSS prephase studies also will end in 2010 with the LSS Concept Review.

After shuttle retirement, the ISS program will enter a new phase where return of hardware to Earth for refurbishment will become increasingly difficult. Although this has already caused an increase in ISS operations costs because of the need to buy new spares, it will help to prepare for LSS operations since there will be a new emphasis on repair and in situ diagnostics, test, and root-cause fault assessment. During the post-space-shuttle ISS operations phase, LSS supportability will work closely with ISS maintenance engineers to fully incorporate ISS lessons learned into the LSS Supportability Implementation Plan, and the ISS will be used as a supportability test bed to the greatest extent possible. During this phase, there will be a strong need to fully fund the supportability technologies discussed in the technology

development roadmap because they will be critical to the overall success of the phased reduction in LSS spares. Prior to LSS SRR, the technologies will have to be defined to a point where the feasibility of the overall LSS supportability approach can be assessed. In addition, these technologies will need to reach TRL 6 by the LSS Preliminary Design Review (PDR). Another key emphasis in this phase will be to push commonality between Altair and LSS and to make sure that these requirements are included in Altair contractual documents.

After robotic and crewed missions to the lunar surface begin, one of the key goals from a supportability standpoint will be to understand the effect of the lunar environment on LSS hardware. This information will be used to validate the failure rate assumptions used in RAM analysis and, if obtained early enough, could be used to influence the designs of the LSS elements. The Altair sortie missions will serve as a final validation of the supportability of LSS elements prior to the start of the outpost Construction phase.

During the initial outpost Construction phase, the main supportability goals will be to maintain the LSS elements once they are delivered to the surface and to test and validate all of the maintenance procedures identified in the LSS supportability concept in Figure 11. During the first few flights, critical spares will be prepositioned at the outpost or brought along on Altair crewed flights, and maintenance will likely be performed at the LRU level. This will be done because the short mission durations will place crew time at a premium and place the emphasis on exploration. As the durations of the missions increase, experiments will be performed to test out lower levels of repair and in situ test and diagnosis. During this time, the condition of the hardware will also be monitored to develop trend analysis for future PdM and ProM planning.

After the outpost is fully constructed and the Permanent Human Presence goal is met, the supportability approach will focus on reducing the resupply mass and determining the effect on other resources such as crew time, power, data, and communications. The lessons learned during this phase will be used to modify LSS hardware if necessary, to help drive requirements for future Mars missions, and to fine-tune the technologies required for outpost self-sufficiency. After the Mars Mission passes PDR, the outpost will be used as a test bed for future exploration, and outpost operations will begin to mirror future exploration operations goals. The spares mass and volume allocated to LSS elements will be reduced to mimic the amounts allowed for the Mars missions, and a long-duration stay of at least 1 year without resupply will be staged on the lunar surface before the Mars Mission begins.

D.6 Supportability of Mars Design Reference Missions

The entire structure of the LSS supportability concept is designed to pave the way for the future exploration of Mars and other destinations. For the Mars Mission, NASA is planning to have one crew and one cargo mission to support a 500-day stay. The Mars Cargo Lander will preposition critical cargo, which will include not only the spares and maintenance equipment but also scientific exploration cargo (including rovers and other elements), life-support gases, crew food and clothing, and everything else necessary to sustain life and support exploration. The Mars crew will have to maintain the hardware elements with little support from Earth, and strict limits on launch mass and volume will mean that everything will be repaired instead of replaced.

Appendix E.—Lunar Surface Systems Repair Scenario

John Easton and Richard Oeftering

There are many scenarios for supportability technologies to consider, and this appendix describes just one example of a mechanical repair on the lunar surface. Developing scenarios allows program planners to evaluate a technology in an operational context. This is similar to the design reference mission (DRM) that is used to evaluate the design of space architectures. By stepping through the scenario in an operational context, supportability can identify activities, resources required (including crew time), infrastructure dependencies, and even sequence dependencies. If competing technologies are considered, then stepping through the basic repair scenario with each technology will expose strengths and weaknesses that would be missed in a simple comparison of operating parameters. The development and evaluation of scenarios is expected to be an ongoing effort.

In the scenario illustrated in Figure 13 and described in the following paragraph, both embedded and process technologies are considered. This scenario describes the process for repairing a damaged undercarriage on a lunar rover.

Damage scenario: While traversing the lunar surface, the rover encounters an apparent rise in the terrain and crosses it at low speed. However, the terrain was actually at the edge of a fragmented rock formation that is obscured by an accumulation of regolith. While the rover is crossing the rise, the underlying rock formation becomes destabilized and the undercarriage strikes and is damaged by rocks released by the formation.

As shown in Figure 14, there are six general steps to conducting this repair. The first step is to protect the rover from further damage, as shown in Figure 15.

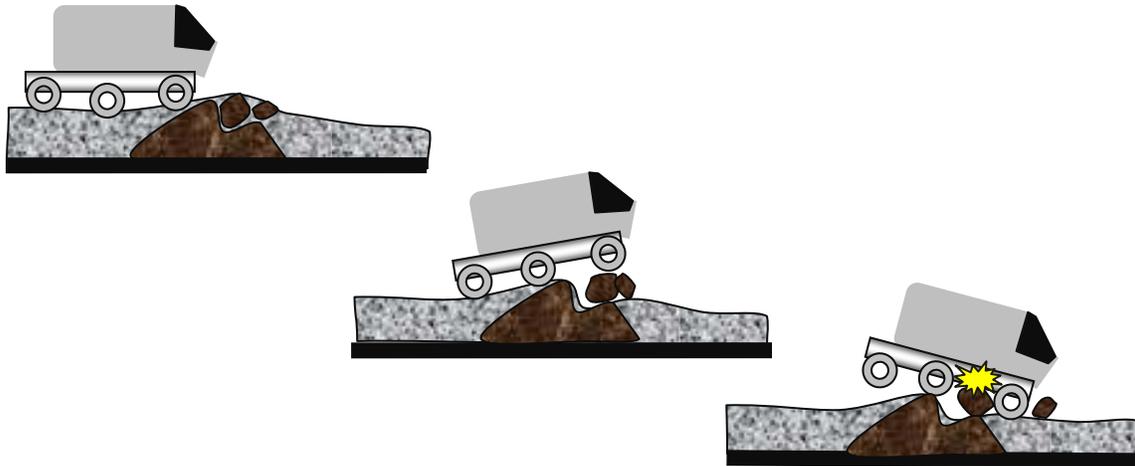


Figure 13.—Lunar rover terrain damage scenario.

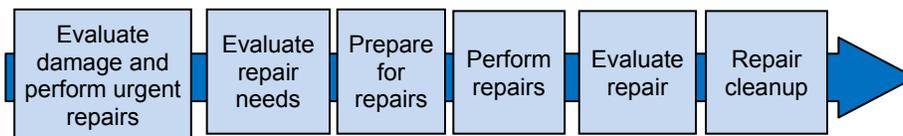


Figure 14.—Overview of the mechanical repair process.

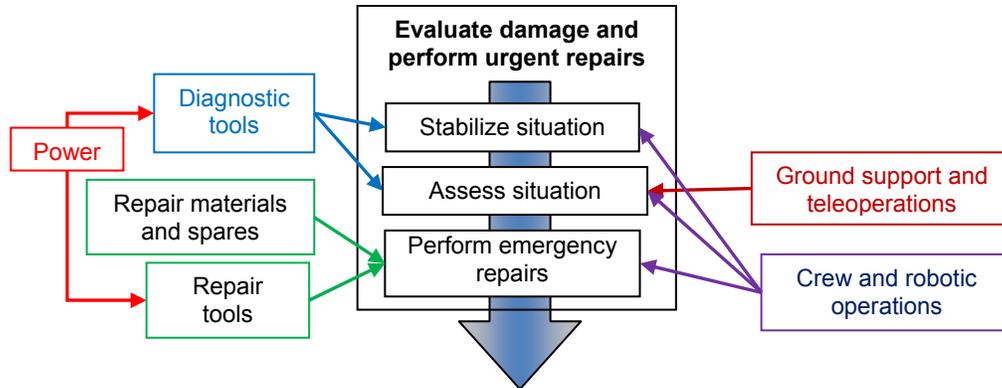


Figure 15.—Steps and resources required for evaluating damage and performing immediate repairs.

E.1 Evaluate Damage and Perform Urgent Repairs

The rover’s automatic systems run diagnostics to determine the immediate condition of the rover and to alert the crew to any pending danger. This could be particularly urgent if the pressurized cabin is damaged. Embedded diagnostics such as an automated pressure leak- and crack-detection system could indicate a hull rupture or a structural crack that would require immediate action.

Diagnostic devices throughout the rover report on damage to a variety of systems, including the suspension, steering, braking, motors, and motor controls. Widespread use of embedded diagnostics minimize the time required for the crew to assess the problem so that they can effectively move into a course of action. These actions require resources, including data links to the ground support teams that assess the situation while the crew performs the physical task of stabilizing the vehicle. The assessment includes images and data from external measurements provided by the crew to augment the diagnostic data stream.

No hull breach is detected, so the next step in the mechanical repair process is to examine the damaged section. The apparent damage involves the vehicle undercarriage between the first and second row of wheels. Crew members attempt to employ the rover’s ability to lift the wheel assemblies to redistribute wheel positions to relieve stress on the damaged undercarriage. One of the six wheel assemblies will not retract when commanded. Motor control data indicates that the mechanism torque and motor currents are over limit because of an apparent jamming of the mechanism. This implies that the wheel assembly will also require repair.

To offload the weight on the wheel assembly for repair, the vehicle needs to be lifted well beyond the wheel’s normal extension range. The vehicle is “jacked” further by a series of steps using the functioning wheel mechanisms, where each wheel is retracted, rocks and regolith are piled under the wheels, and the wheels are extended until the jammed wheel is clear of the ground. For safety, the crew eventually scavenges parts from an earlier mission lander to create “jack stands” to support the undercarriage. This requires cutting and welding with electron-beam (E-beam) equipment. With great difficulty, the crew removes the jammed wheel assembly from the vehicle.

E.2 Evaluate Repair Needs

As part of the evaluate repair needs activity shown in Figure 16, ground support teams need photos of the damaged area of the rover undercarriage from a variety of angles. These photos will show the extent of the damage to the undercarriage itself as well as to attached parts and adjacent areas. The crew uses a robot to manipulate a camera and view the underside of the vehicle out of reach of the crew. An x-ray source and detector are installed on the pair of manipulators to allow the crew to examine the metal structure for hidden cracks or other damage. The use of the robotic manipulator also prevents the crew from being exposed to x rays.

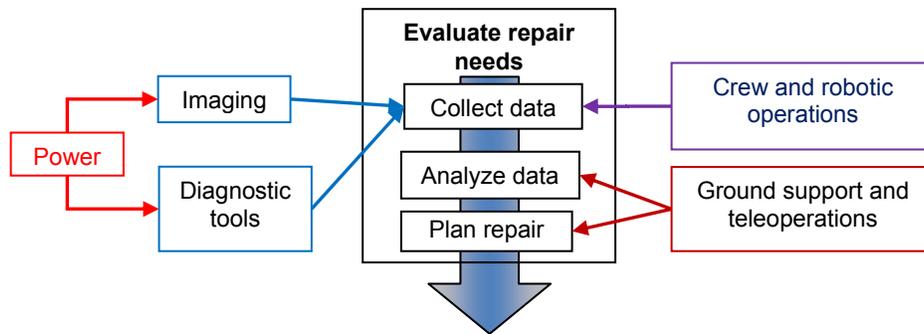


Figure 16.—Steps and resources required to evaluate repair needs.

Data and imaging are relayed to both the crew and the ground support teams. With this three-dimensional computer-aided design (CAD) model data of the rover, and the operational experience of crew members and ground controllers, the team formulates a plan to repair the undercarriage using the tools and materials at hand on the lunar surface.

In this scenario, x-ray and embedded automated leak- and crack-detection instruments do not reveal cracks or cabin leakage. Except for obvious surface scrapes, the structure appears to be sound. The great difficulty in removing the jammed wheel assembly is of great concern because it implies that the wheel, the undercarriage, or both have been distorted. A functional check of the wheel assembly shows it to be fully functional with normal motor torque values. A dimensional check at key points indicates that the assembly alignment is true. However, a check of the undercarriage mounting hard points indicates that the fastener holes will not line up.

A robot with dimensional profiling instruments performs a physical touch-off of the undercarriage to determine the actual geometry. The touch-off measurements are compared with the as-built, three-dimensional CAD model, and the problem is determined to be a local distortion of the undercarriage frame near the mounting points of the wheel assembly. The distortion, a longitudinal bend and twist, has put very high loads into the wheel assembly attachment, causing the suspension and extension mechanisms to jam. This also explains the misalignment of the mounting holes.

Straightening the frame is considered, but it would require extensive disassembly, including removal of the cabin assembly. The integrity of a number of fluid and electrical systems would be violated, and this would further consume the crew's remaining time at the expense of mission objectives. Furthermore, the deintegration of undamaged systems, including life support, is deemed to be too risky. The alternative chosen is to modify the frame with an in situ fabricated adapter.

The team develops the following plan:

- Using metal scavenged from the previous lander, they will fashion metal plates into a wedge-shaped shim plate to correct the local alignment and serve as a new attachment point. Electron beam free-form fabrication (EBF3) will be used to modify the metal plate to reinforce it and provide the shim profile.
- Bolts scavenged from the lander will be modified and E-beam welded to the adapter as mounting studs. This also will simplify the reinstallation of the wheel assembly.
- The shim plate will be fabricated in a scavenged logistics module that had been converted to serve as an onsite, unpressurized repair and fabrication depot to support robotic cutting and welding equipment.
- Fabrication of the adapter will be programmed offline using robotic simulation tools.
- Cutting and welding operations will be performed by a robot-mounted E-beam system.
- The plan will involve cooperation between the robotics and the crew.

The complete operation is developed and simulated in three-dimensional graphics and with a physical analog of the actual hardware. Imaging and dimensional data of the damaged area are used to modify the original CAD models and to develop the robotic welding operation that will weld the adapter in place. Robotics will be essential because, aside from safety issues, the welding will require significant skill and a steady coordinated movement. This cannot be done effectively by a crew member encumbered with a stiff, pressurized suit.

The three-dimensional model is used to plan the motion of the robot-mounted E-beam welding unit. This includes controlling the position and orientation of the E-beam aperture at every point along the weld path. The metal wire feed rates and beam energy levels have been preprogrammed for the process equipment. The ground team uses these data to evaluate the design limitations of the rover, assessing the need to limit future operations. Since the adaptor is a permanent change to the rover, the CAD data of the modifications are used to update the rover configuration drawings.

E.3 Prepare for Repair

In the preparation for repair activity shown in Figure 17, the crew manually cuts appropriate pieces from metal stock scavenged from a previous lander. The rough-cut pieces require additional cutting and trimming to size. The E-beam gun is reconfigured to operate with gaseous oxygen, effectively creating a plasma cutter, which is used to cut the stock pieces to size. Robots cut the pieces using a robotic program developed offline. Robots also position and weld the bolts to the plates. An adapter made entirely by EBF3 technique is considered, but for this repair, a hybrid part is made from scavenged machined components that are modified by and integrated with EBF3.

Using additional scavenged metal, the crew weld and install a custom temporary fixture to position and hold the new metal piece in place on the damaged undercarriage. This also prevents any movement of the hardware during welding. Crew and robot time are needed to physically set up the equipment. Crew time is minimized by offline programming of the robotic equipment.

The robot is refitted with the E-beam welder and with a precision positioning unit for precise manipulation of both the beam and wire feed unit. The support infrastructure includes process-monitoring equipment, such as cameras, temperature measurement, and other instruments for use during the welding process. The support infrastructure also provides power to the various instruments and communications and data links to the crew and ground support teams. These data links allow the ground support teams to upload the welding process plans formulated earlier. Finally, the crew installs consumable materials, such as the weld filler wire.

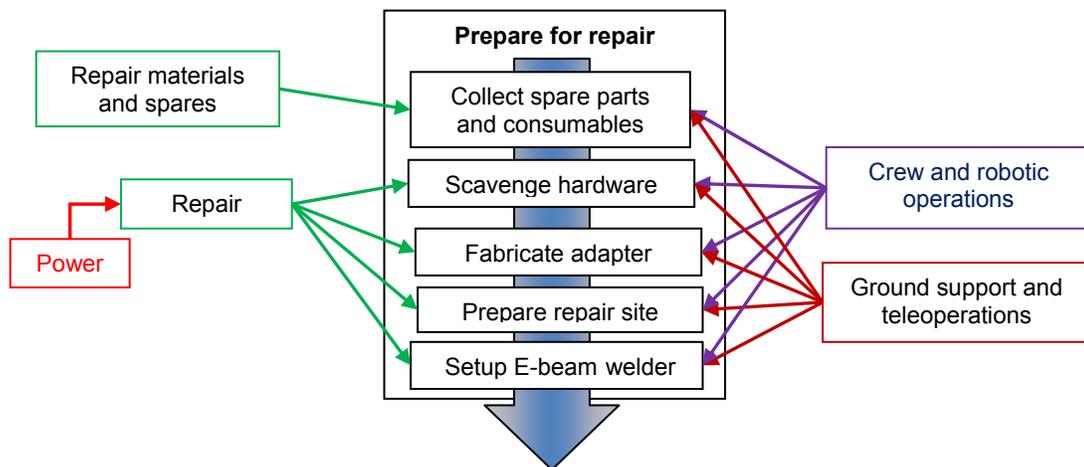


Figure 17.—Steps and resources required to prepare for mechanical repairs.

E.4 Perform Repair

In the performance of the repair, as shown in Figure 18, ground support teams, and possibly crew members on the lunar surface, activate the process sequence that was developed and uploaded in earlier steps. Although a robot can move through a preprogrammed path more precisely than a human, it may lack the precision required for an E-beam. Therefore, the weld gun is supported by a precision positioning system that serves as a robotic extension that can compensate for any errors in the main robot's motion. Welding of the adapter is rapid, being completed in less than one minute. Process parameters—including wire feed rate, motion speed, E-beam current, and beam aperture—are executed automatically. The ground support and lunar surface teams monitor the progress of the welding operation via monitoring systems, such as cameras and temperature-measurement instruments, which had been integrated into the welding system.

This step in the repair process will require significantly more resources than the other steps. Welding will require a significant amount of peak power, but the duty cycle will be short. Depending on the weight and speed of the robot and positioning equipment, drive motors may make up a substantial portion of the peak power demand.

Direct physical intervention will be unlikely; however, the crew will be able to execute an emergency stop should the weld process malfunction. Because of the criticality of the process to the overall mission and crew safety, the process will be monitored by both crew and ground support. Because of the communications delay, the crew (rather than ground support) will provide the primary emergency stop action.

E.5 Evaluate Repair

Inspections conducted after the welding process for the new undercarriage support is complete will verify the effectiveness of the repair. If needed, the crew will conduct additional touchup work on the weld. The steps and resources required for this are shown in Figure 19.

The crew replaces the E-beam welder with the portable x-ray apparatus, reusing the translation equipment. Both an x-ray source and detector have to be positioned for each x-ray snapshot of the new welded assembly. The ground support teams analyze these data for weld flaws, and the crew checks the position and alignment of the hardware.

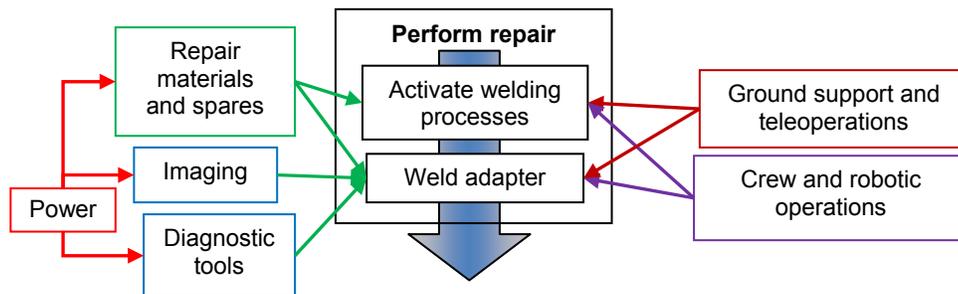


Figure 18.—Steps and resources required to execute the repair.

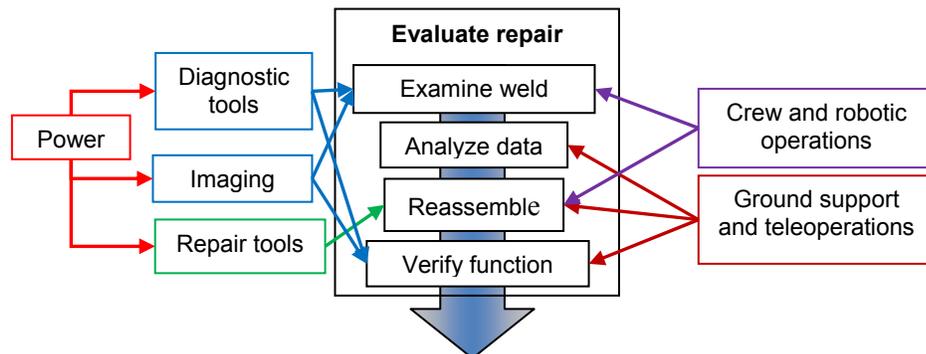


Figure 19.—Steps and resources required to evaluate a mechanical repair.

The resources for this final step are similar to those required for diagnosing the extent of the damage earlier. Because the results are acceptable, any temporary weld support fixtures are removed. At this point, the crew reinstalls the wheel assembly and verifies its functional operation.

The repaired rover is checked over, and the crew conducts a test drive to further test the rover functions and to reveal any other damage. After completing the vehicle-level checkout, the crew concludes the repair by stowing equipment, tools, and unused consumables. The crew cleans the area around the repair site and disposes of the waste, as needed. Then the repaired rover is returned to service, and the crew resumes its mission.

E.6 Time Resources

Such repairs would require the use of many resources, including some with high peak demand, including crew and/or robot time, power, imaging, and measurement data. Figure 20 shows estimates of the amount of time required by ground support teams as well as by crew or robots during this mechanical repair scenario. These time estimates arose from the engineering experience of the authors and cannot be regarded as having sufficient fidelity to be used as design information. Fidelity is expected to improve as functional prototypes of LSS equipment become available and are tested in relevant Lunar Outpost simulations.

In general, most of the time resources spent in repairs will be used by the ground support teams. They will analyze data on the damaged parts, prepare a repair plan, analyze the results of the repair, and ensure that the damaged rover is returned to full service. Crew or robotic surface time will be required most extensively while preparing, conducting, and evaluating the repair. On the basis of these estimates, the total surface repair time required by robots and/or crew would be 7.5 hr, whereas the ground support teams would spend 35 hr (roughly 5 times the crew hours) for this repair.

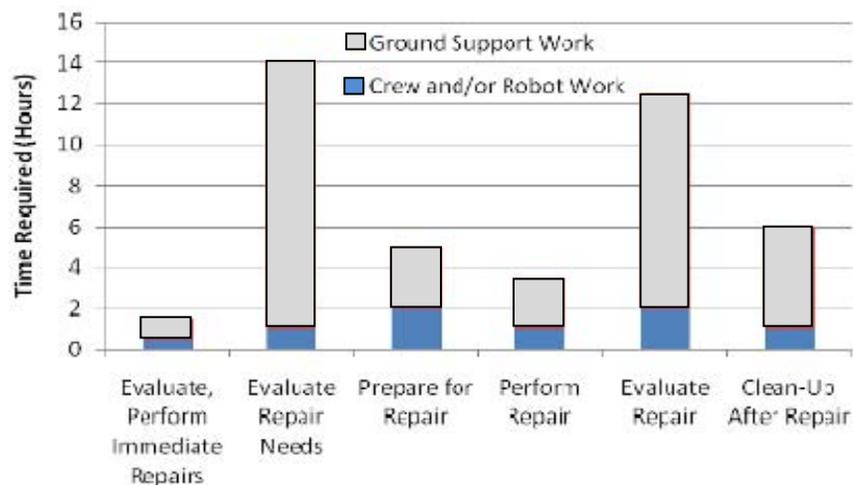


Figure 20.—Crew and ground support time estimates for the various stages of the repair scenario.

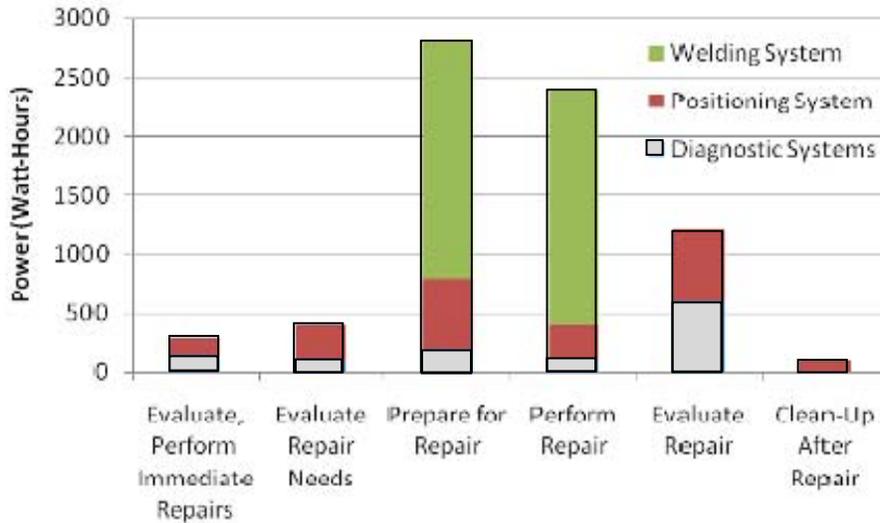


Figure 21.—Estimate of power required for the mechanical repair.

E.7 Power Resources

The second critical resource considered was the power required for this repair. Figure 21 shows estimates of the power required for each step in the mechanical repair. As in the case of crew time, the power profile estimates cannot be regarded as having sufficient fidelity to be considered as design data. The graph shows the power used in each step of the overall process of welding the new adapter and of welding it to the vehicle.

The primary loads are

- E-beam welding (and cutting)
- Precision positioning and robotic motor loads
- Diagnostic systems, including optical measurements, x ray, and video

E-beam loads are high but appear only in two phases. The combined precision positioning and robotic loads appear in every phase. Diagnostic and analysis loads appear in all but the final cleanup phase. The total repair requires 7200 W-hr, with the peak use of the welding apparatus requiring 3000 W, used intermittently over the course of 1 hr.

E.8 Supportability Technologies Employed

The supportability technologies used directly or providing a supporting role in this scenario follow:

- Embedded technologies
 - Automated leak and crack detection
 - Power component diagnostics
 - Recyclable structures
- Process technologies
 - SI
 - Optical measurement
 - X-ray imaging
 - Structural element scavenging

- Material cut and sizing techniques
- E-beam welding
- Precision positioning

This scenario is the first of many that will be developed as part of the Supportability Project formulation process. Scenarios like this will be coupled with system-modeling tools that will further refine the needs and identify and quantify dependencies for supportability technologies.

Appendix F.—Acronyms

AdvECLSS	Advanced Environmental Control and Life Support System
AFRL	U.S. Air Force Research Laboratory
AM	Ascent Module
ATP	acceptance test procedure
ATU	Audio Terminal Unit
BGA	ball-grid array
BIT	built-in test
CAD	computer-aided design
CARD	Constellation Architecture Requirements Document
CDK	chassis driving kit
CDR	Critical Design Review
CLEAR	Component-Level Electronic-Assembly Repair
CM	configuration management (Figure 5)
CM	corrective maintenance (text and other figures)
CM	Crew Module (Figure 6)
CMC	Chariot Mobility Chassis
Comm	communications
Comps	components
Cor Hab	Core Habitat
COTS	commercial orbital transportation system
CRE	Component Repair Experiment
Crit	criticality level
CVIU	common video interface unit
CxP	Constellation Program
DCR	Design Concept Review
DM	Descent Module
DPLM	Disposable Pressurized Logistics Module
DRM	design reference mission
DTV	diagnostics, test, and verification
E-beam	electron beam
EBF3	electron beam free-form fabrication
EBM	electron beam melting

ECLSS	Environmental Control and Life Support System
EDS	Earth Departure Stage
EOL	end of life
EPO	education and public outreach
ESD	electrostatic discharge
ETDP	Exploration Technology Development Program
ETU	engineering test unit
EVA	extravehicular activity
Ext	external
FFF	free-form fabrication
FIB	focused ion beam
FMEA	failure modes and effects analysis
FOD	foreign object damage
FPGA	field-programmable gate arrays
FRR	Flight Readiness Review
FTA	fault tree analysis
FY	fiscal year
GSE	ground support equipment
Hab 1	Lunar Habitat 1
HLR	Human Lunar Return
HRM	high-rate multiplexer
IC	integrated circuit
IDMM	intermediate and depot maintenance manual
IF	intermediate frequency
ILS	integrated logistics support
Int	internal
I/O	input/output
IP	international partners
ISRU	in situ resource utilization
ISS	International Space Station
IVA	intravehicular activity
KT	linear increasing failure rate (math variable in reliability analysis)
LAS	Launch Abort System
LCT	Lunar Communication Terminal

LED	light-emitting diode
LEO	low Earth orbit
LER	Lunar Electric Rover
LL	Lunar Lander
LLO	low lunar orbit
LOC	loss of crew
LRU	line replaceable unit
LSS	Lunar Surface Systems
M&R	maintenance and repair
MCT	mobile communications terminal
MDM	Multiplexer/Demultiplexer Module
MEMS	microelectromechanical systems
MPU	Mobile Power Unit
MTTR	mean time to repair
NAVAIR	Naval Air Systems Command
NAVSEA	Naval Sea Systems Command
NH ₃	ammonia
NSLD	NASA Shuttle Logistics Depot
NSSD	NASA Spacecraft Services Depot
O ₂	molecular oxygen
OEM	original equipment manufacturer
OPA	ortho-phthalaldehyde
OPS	operations
ORU	orbital replacement unit
OSE	outpost support equipment
PCB	printed circuit board
PC&S	production control and scheduling
PDA	personal digital assistant
PdM	predictive maintenance
PDR	Preliminary Design Review
PM	preventative maintenance
PnP	plug and play, or Plug-N-Play Satellite project of the Air Force
PRACA	Problem Reporting and Corrective Action
ProM	proactive maintenance

PRR	parts rework replacement
PRT	prevention resolution team
PSU	power and support unit
QE	quality engineering
R&R	remove and replace
RA	Robotic Assistant
RAM	reliability, availability, and maintainability
RC	root cause
RCFA	root cause fault analysis
RE	reliability engineering
RF	radiofrequency
RFID	radiofrequency identification
RFP	request for proposal
RPCM	Remote Power Controller Module
RPLM	Reusable Pressurized Logistics Module
RTOK	Retest OK
S&R	scavenge and recycle
SA	Spacecraft Adapter
SARD	Surface Architecture Reference Document
SBIR	Small Business Innovation Research
SDR	System Design Review
SGTRC	Space-to-Ground Transmitter Receiver Controller
SI	synthetic instrument
SM	Service Module
SMT	surface-mount technology
SoRGE	Soldering in Reduced Gravity Experiment
SPR	Small Pressurized Rover
SRB	solid rocket booster
SRR	System Requirements Review
SRU	shop replaceable unit
SSU	Structural Support Unit
STIM	Smart Transducer Interface Module
SWP	size, weight, and power
TBD	to be determined

TEDS	Transducer Electronic Data Sheet
Tri-ATHLETE	Three-legged All-Terrain Hex-Legged Extraterrestrial Explorer
TRL	Technology Readiness Level
TT&E	test teardown and evaluate
UA	unexplained anomaly
USB	universal serial bus
UV	ultraviolet
VBSP	video baseband signal processor

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14. ABSTRACT The Lunar Surface Systems Supportability Technology Development Roadmap is a guide for developing the technologies needed to enable the supportable, sustainable, and affordable exploration of the Moon and other destinations beyond Earth. Supportability is defined in terms of space maintenance, repair, and related logistics. This report considers the supportability lessons learned from NASA and the Department of Defense. Lunar Outpost supportability needs are summarized, and a supportability technology strategy is established to make the transition from high logistics dependence to logistics independence. This strategy will enable flight crews to act effectively to respond to problems and exploit opportunities in an environment of extreme resource scarcity and isolation. The supportability roadmap defines the general technology selection criteria. Technologies are organized into three categories: diagnostics, test, and verification; maintenance and repair; and scavenge and recycle. Furthermore, "embedded technologies" and "process technologies" are used to designate distinct technology types with different development cycles. The roadmap examines the current technology readiness level and lays out a four-phase incremental development schedule with selection decision gates. The supportability technology roadmap is intended to develop technologies with the widest possible capability and utility while minimizing the impact on crew time and training and remaining within the time and cost constraints of the program.				
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