7. Operations

7.1 Ground Operations

The Exploration Systems Architecture Study (ESAS) team addressed the launch site integration of the exploration systems. The team was fortunate to draw on expertise from members with historical and contemporary human space flight program experience including the Mercury, Gemini, Apollo, Skylab, Apollo Soyuz Test Project, Shuttle, and International Space Station (ISS) programs, as well as from members with ground operations experience reaching back to the Redstone, Jupiter, Pershing, and Titan launch vehicle programs. The team had a wealth of experience in both management and technical responsibilities and was able to draw on recent ground system concepts and other engineering products from the Orbital Space Plane (OSP) and Space Launch Initiative (SLI) programs, diverse X-vehicle projects, and leadership in NASA/Industry/Academia groups such as the Space Propulsion Synergy Team (SPST) and the Advanced Spaceport Technology Working Group (ASTWG).

7.1.1 Ground Operations Summary

The physical and functional integration of the proposed exploration architecture elements will occur at the primary launch site at the NASA Kennedy Space Center (KSC). In order to support the ESAS recommendation of the use of a Shuttle-derived Cargo Launch Vehicle (CaLV) and a separate Crew Launch Vehicle (CLV) for lunar missions and the use of a CLV for ISS missions, KSC's Launch Complex 39 facilities and ground equipment were selected for conversion. Ground-up replacement of the pads, assembly, refurbishment, and/or processing facilities was determined to be too costly and time-consuming to design, build, outfit, activate, and certify in a timely manner to support initial test flights leading to an operational CEV/CLV system by 2011. (Reference **Section 12**, **Cost**.) The ESAS team also performed a detailed examination of Launch Vehicle (LV) options derived from the Evolved Expendable Launch Vehicle (EELV) configurations options in support of the study. The results of those analyses and a technical description of the vehicle configurations considered can be found in **Section 6**, **Launch Vehicles and Earth Departure Stages**. For a description of the EELV-derived concepts of operation, refer to **Appendix 7A**, **EELV Ground Operations Assessment**. **Section 12**, **Cost**, provides the cost estimation results.

For similar cost- and schedule-related reasons, conversion of key facilities at KSC's Industrial Area is recommended for Crew Exploration Vehicle (CEV) spacecraft assembly and integration. The existing capabilities for human spacecraft processing are such that there was found to be no need to spend large amounts of resources to reproduce and construct new facilities to support the CEV.

The ESAS team began its architectural definition by defining reference concepts of operations that addressed the following: (1) CEV spacecraft assembly and checkout; (2) CLV and heavy-lift CaLV assembly; (3) CLV and CaLV space vehicle integration and launch operations; and (4) recovery and refurbishment operations of the reusable Solid Rocket Booster (SRB) and Crew Module (CM) elements. Indirect functions and infrastructures (e.g., facilities maintenance, flight and ground system logistics, support services, and sustaining engineering) were defined to support these operations as outlined in detail in **Appendix 7B**, **Concepts of Operations and Reference Flows**.

Cost-estimation analyses, which are detailed in **Section 12**, **Cost**, addressed the direct operations costs as well as the aforementioned infrastructure functions. Contemporary management and operations methods were assumed with no credit taken in the estimates for incorporating new methods. While it is anticipated that opportunities to incorporate new methods will be seized upon, the ESAS team believes NASA should demonstrate savings as the program progresses rather than promise savings at the program's outset. Advanced concepts for improving NASA's annual support costs for infrastructure consolidation, more efficient work control systems, and more advanced Command and Control (C&C) systems are addressed below.

The level of nonrecurring conversion work and recurring launch processing work will be highly dependent on the complexity of the flight system interfaces with the ground systems. Ground architecture conversion costs, conversion schedule, and annual recurring operations costs are highly dependent on the management process controlling the number and complexity of the flight-to-ground interfaces. Wherever possible and whenever practical, the study team searched for means to control these interfaces in the ESAS concepts and searched for innovative means to manage and contain their growth in the ESAS requirements emerging from the study. The following is a list of ESAS operability design drivers for management and control during design:

- Total number of separate identified vehicle systems;
- Total number of flight tanks in the architecture;
- Number of safety-driven functional requirements to maintain safe control of systems during flight and ground operations;
- Number of unplanned tasks;
- Number of planned tasks;
- Total number of required ground interface functions;
- Total number of active components;
- Number of different required fluids;
- Total number of vehicle support systems with element-to-element interfaces;
- Number of flight vehicle servicing interfaces;
- Number of confined/closed compartments;
- Number of commodities used requiring Self-Contained Atmospheric Protection Ensembles (SCAPE), medical support, and routine training;

- Number of safety-driven limited access control operations;
- Number of safing operations at landing;
- Number of mechanical element mating operations (element-to-element and element-to-ground);
- Number of separate electrical supply interfaces;
- Number of intrusive data gathering devices; and
- Number of Criticality 1 (Crit-1) system and failure analysis modes.

Additional detail, including key benchmarks, is provided in **Appendix 7C**, **ESAS Operability Design Drivers**.

The ESAS team also imposed a requirement for the gradual removal of hazardous and toxic commodities in time for the lunar program. This requirement states: "The Exploration Architecture subsystems, which require new development, shall not use expended toxic commodities." It further states "that the Exploration Program will develop a plan for legacy subsystems to eliminate use of any expended toxic commodities." (Refer to **Appendix 2D**, **ESAS Architecture Requirements**.) Specification of these commodities in flight systems requires expensive infrastructure capable of safely conducting such operations. The use of toxic commodities requires ground personnel working with these systems to wear special SCAPE suits, complicates launch facility design, slows down processing cycle times, imposes personnel hazards, and drives up infrastructure and logistics support costs. Examples are provided in **Appendix 7D**, **Toxic, Hazardous Operations Impacts**. While the ESAS cost estimates assumed that hazardous and toxic propellant servicing may be required for the initial LV, a technology integration plan was developed to eliminate the use of toxic commodities for the lunar missions and beyond as outlined in **Section 9**, **Technology Assessment**.

The ESAS team also recommended quantitative methods for managing and controlling critical flight and ground system design characteristics that pose ground operations and support risks (both safety hazard and cost risks) similar to the way flight system weight and flight performance are managed during traditional design processes. This "design-for-support" approach complements the traditional requirement for the launch site to support the design and is intended to create a more effective architecture for NASA that is safer, simpler, more affordable, and more dependable to develop, operate, and sustain.

7.1.2 Reference Ground Architecture Description

7.1.2.1 Flight System Assumptions

The ESAS examined various space vehicles for replacement of the Shuttle Orbiters as a means for human access to space. Much like today's Shuttle system, the ESAS reference architecture is also a partially reusable system and was selected from an array of options after a careful review of various risk factors, including crew safety, performance, and overall economy.

The chosen ESAS reference mission architecture calls for a "1.5-launch solution" for crewed lunar missions that use a Shuttle-derived CaLV to launch a Lunar Surface Access Module (LSAM) attached to an Earth Departure Stage (EDS). This is followed by the launch of a single four-segment SRB-derived CLV and a new upper stage propelled by a single Space Shuttle Main Engine (SSME) fed by Liquid Oxygen (LOX) and Liquid Hydrogen (LH2). The trade studies leading to the selection of this approach and a detailed definition of the selected elements are provided in **Section 4**, **Lunar Architecture** and **Section 6**, **Launch Vehicles and Earth Departure Stages**.

A critical element of the proposed architecture is the launching of the CEV on top of the CLV rather than a side-mounted approach. The integrated CEV spacecraft is composed of a reusable CM, an expended Service Module (SM) that houses support services such as power and in-space propulsion, and a Launch Abort System (LAS) that is nominally jettisoned and allows the crew a safe option for avoiding catastrophic LV events. A lunar CEV capsule can accommodate a nominal crew of four personnel. Configured for an ISS mission or future Mars mission scenarios, the CM can support a crew of six. The trade studies leading to the selection of this approach and a detailed definition of the systems are provided in **Section 5**, **Crew Exploration Vehicle**.

7.1.2.2 Concept of Operations Overview and Approach

The approach used to define the operations concept was to identify generic launch site functions and relate these to each flight hardware element and major assembly. Previous engineering efforts in this area, led by KSC, were used in this study. A more detailed definition of the generic functions drawn on by the ESAS team is provided in **Appendix 7E**, **Generic Ground Operations and Infrastructure Functions**.

The approach of relating the flight elements and major assemblies to the generic ground operations is depicted pictorially for the CEV/CLV space vehicle in **Figure 7-1** and for the LSAM/CaLV space vehicle in **Figure 7-2**. The figures show the flight hardware elements arriving at the launch site on the left side. From left to right, each figure follows the hardware conceptually as it arrives and goes through the various functions of a launch operation. The concept of operations diagram provides a structure to define: (1) the arrival concept; (2) the flight element receiving, assembly, and/or storage concept; (3) the vehicle integration concept; (4) the launch concept; and (5) the post-launch element recovery and reuse concept (if applicable). More detailed descriptions of the launch operations concepts in **Figure 7-1** and **Figure 7-2** are found in **Section 7.1.2.2.3**, **Reference Architecture Ground Processing Description.**

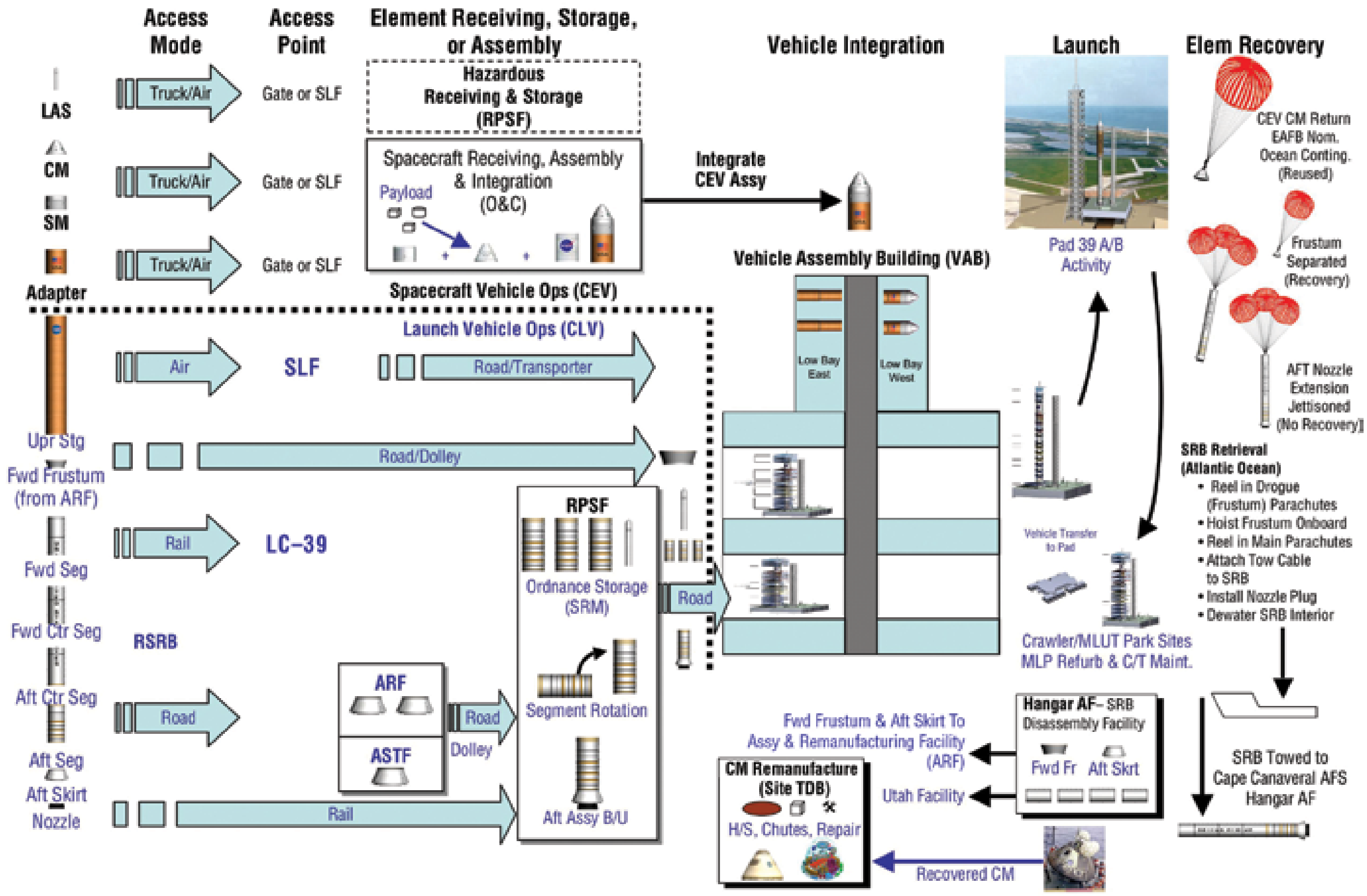


Figure 7-1. Defining the CEV/CLV Operations Concept

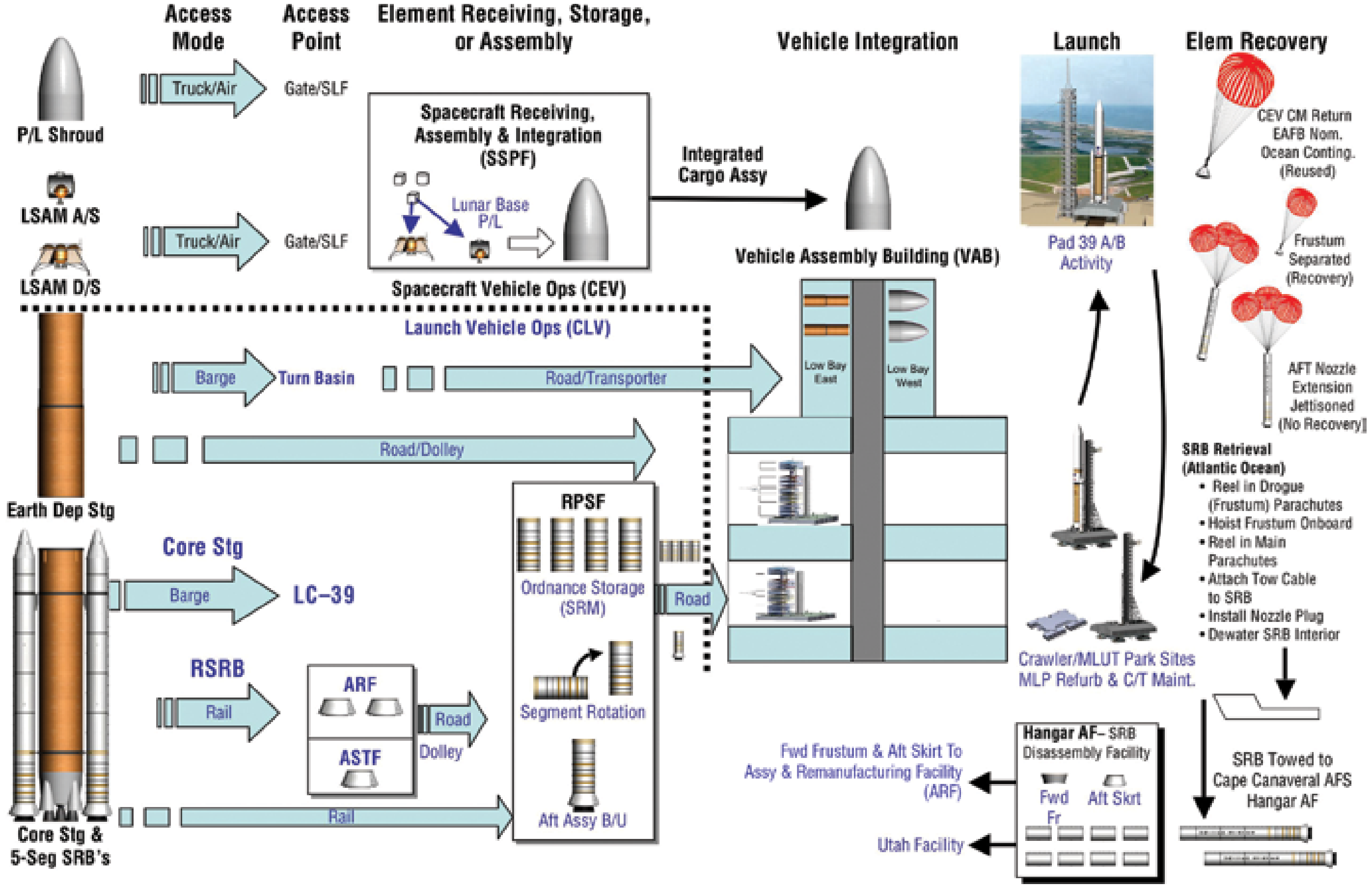


Figure 7-2. Defining the LSAM/CaLV Operations Concept

The association of the generic processing operations (i.e., operations headings along the top of the figures) with specific ESAS flight hardware elements and assemblies under consideration enabled a structured process for defining ESAS-specific tasks, leading to a preliminary operations concept. The fundamental objective of the operations concept is to define a safe and efficient ground-based process that produces routine and safe human space flights for the flight crew and high-value cargo. Creating an efficient operations concept involves working with the vehicle design teams to minimize the number and complexity of flight elements to help reduce the resulting required ground functions and, therefore, avoid the traditional accumulation of ground tasks from the beginning. This part of the study required insight into potential interfaces between the proposed flight hardware elements and the resulting accumulated need for ground facilities, Ground Support Equipment (GSE), and software. Thus, as various LV and spacecraft concepts were assessed, identifying potential ground interfaces was an important task in the ESAS effort.

The importance of spending the time to conduct an analysis of flight-ground interfaces and the trading the resulting system concepts was recognized early in the history of human space flight: "…the von Braun team preached and practiced that rocket and launch pad must be mated on the drawing board, if they were to be compatible at the launching. The new rocket went hand in hand with its launching facility." (Moonport: A History of Apollo Launch Facilities and Operations, NASA SP–4204; Benson & Faherty, 1978).

Analyzing flight-to-ground interfaces produced several design characteristics as important discriminators in the study. The ground interface sensitivities depended on the number of flight elements, the relative complexity of the proposed upper stage, whether or not the current SRB aft skirt interfaces are maintained, and the requirement for local manual access at the pad for SRB Safe and Arm (S&A) device operation prior to launch. The number and type of main propulsion engines and turbo pumps, the engine start cycle, engine operating cycle, and tank arrangements were assessed for resulting upper stage subsystem and ground operations complexity. Recent benchmarking assessments of various engine/propulsion designs by the Government/industry/academia SPST helped to assess relative operational complexity and dependability.

As an example of the importance of this type of LV-to-launch site compatibility analysis, one EELV-derived heavy-lift concept under consideration would have required a flame deflector width and depth so large that even the Pad 39 flame trench would have needed to be greatly enlarged. This would have in turn required a mobile launcher so wide that Vehicle Assembly Building (VAB) high bay dimensions would be called into question and a different crawler transporter would be required to straddle the trench, thus requiring a new crawler way. Upon further study, it was obvious that the LV system concept was incompatible with reasonable ground architecture investments and study constraints.

7.1.2.2.1 Revisiting the "Clean Pad" Concept

The ESAS team had previously conducted assessments of various launch concepts and determined that the integrate-transfer-launch concept, or "mobile launch" concept, was the preferred approach for the Shuttle-derived concepts. What was recommended, however, was a KSC Complex 39 mobile launch concept with less overall accumulated infrastructure to operate and maintain.

7.1.2.2.2 Complex 39 Historical Background

The origin of the mobile launch concept with a clean pad goes back to at least the German rocket team led by Wernher von Braun during the 1930s and the Second World War. Adopted for tactical missile operations, the clean pad design approach has been continually pursued as an objective in the U.S. for larger-scale space flight since the Air Force's Advanced Launch System (ALS) studies of the 1980s. This design approach assumes that prelaunch assembly and servicing of the LV and spacecraft occur away from the launch point and that only propellant loading and final countdown operations are required, without the need for large access and auxiliary service equipment, subsequent to positioning for launch. If a failure requiring intrusive personnel access to the space vehicle occurs, the vehicle is quickly rolled back to its assembly and servicing facility. The design characteristics essential to making this approach work are simple automated vehicle-to-ground interfaces, minimal personnel access requirements at the pad, and dependable flight hardware and launch pad systems. The clean pad mobile launch concept was, in fact, the original design approach for the Apollo-Saturn Launch Complex 39, as shown in **Figure 7-3**. However, due to late design issues associated with Apollo spacecraft servicing, a massive Mobile Service Structure (MSS), shown in **Figure 7-4**, complicated the pad operations and maintenance for Apollo launches. During the course of this study, it was often helpful to the team to refer to Apollo-Saturn launch operations. **Appendix 7F**, **Apollo-Saturn V Processing Flows** is provided as an example of a processing flow of an Apollo-Saturn space vehicle and its countdown.

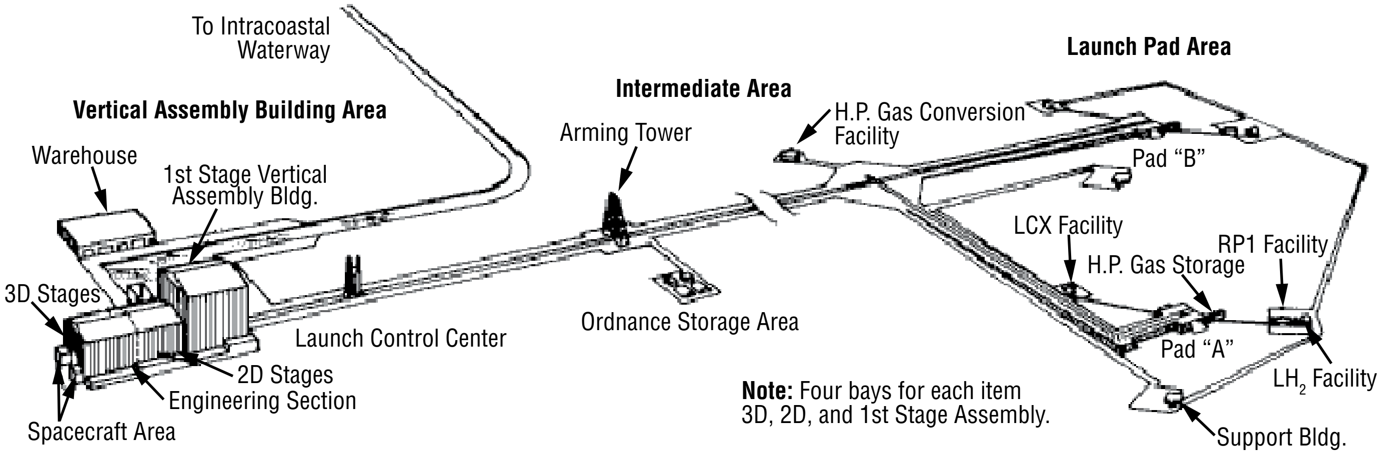


Figure 7-3. Saturn Mobile Launch Concept, July 1961

Figure 7-4. Saturn-Apollo MSS

A second opportunity for NASA to implement the clean pad approach during the conversion of Launch Complex 39 for the Shuttle program was again complicated by late pad access requirements that drove the design of a very complex Rotating Service Structure (RSS) fixed permanently to the apron. Additionally, many of the flight-to-ground propellant service arms and umbilicals were removed from the mobile platform and fixed to a permanent tower on the pad (the Fixed Service Structure (FSS)). The entire ground design began to revert back to the older approach of assembling and mating pad-to-vehicle interfaces at the pad while still maintaining the same VAB infrastructure and an internally complex Mobile Launch Platform (MLP). For example, what had been portable hypergolic servicers during Apollo became permanent equipment fixed within the pad perimeter topped by open canopies. What ultimately emerged at Complex 39 as the vehicle needs became more defined was more than a relocation of infrastructure from the Mobile launcher to the pad—it was simply more total infrastructure.

Since a modern, large-scale clean pad design was successfully implemented on Pad 41 for the USAF/Lockheed Martin Atlas V launch system, the ESAS team concluded that NASA should also return to its original desire to build a clean pad at Complex 39. The chosen concepts use a near-clean pad by building a much less complicated tower for personnel access, lightning protection, and flight crew emergency egress—all relatively passive in design when compared to complex propellant umbilicals and swing-arms. In the ESAS concepts, these services are affixed to a Launch Umbilical Tower (LUT) that is, in turn, attached to and MLP. Not only is the space vehicle assembled indoors, the space vehicle-to-ground interfaces are also mated, checked, and prepared for launch within the protection of the VAB. This approach returns the VAB to its original purpose of serving as an enclosed facility for personnel to prepare a space vehicle prior to a short and highly automated set of actions at the launch pad.

7.1.2.2.3 Reference Architecture Ground Processing Descriptions

Descriptions of the reference ground operations approach for both the CEV/CLV and the LSAM/CaLV are provided below. The cost estimates for launch site labor and facility needs assumed the worst-case, most facility-intensive, work-intensive flows found in **Appendix 7B**, **Concept of Operations and Reference Flows**, while the reference-targeted approach is the more streamlined set of processes depicted in **Figure 7-1** and **Figure 7-2**.

Reference CEV/CLV Processing Description

While the CLV pad concept draws on Saturn-Apollo, much of the ground hardware will come from the Space Shuttle program. Three Space Shuttle MLPs are available to convert to CLV Mobile Launch Umbilical Towers (MLUTs). Additionally, the FSS can be simplified and extended to accommodate the CLV. More detailed design activity must occur before final decisions are made on whether the personnel access and crew emergency egress functions of the FSS should be combined with the umbilical tower and located on the MLUT (as was done during Apollo), or whether program constraints dictate that it should remain fixed to the pad (its current configuration for Shuttle).

The ESAS team has recommended a reference operations concept for the CEV/CLV space vehicle. A reference processing flow is described below for crewed flights and follows the numbered elements in **Figure 7-5**.

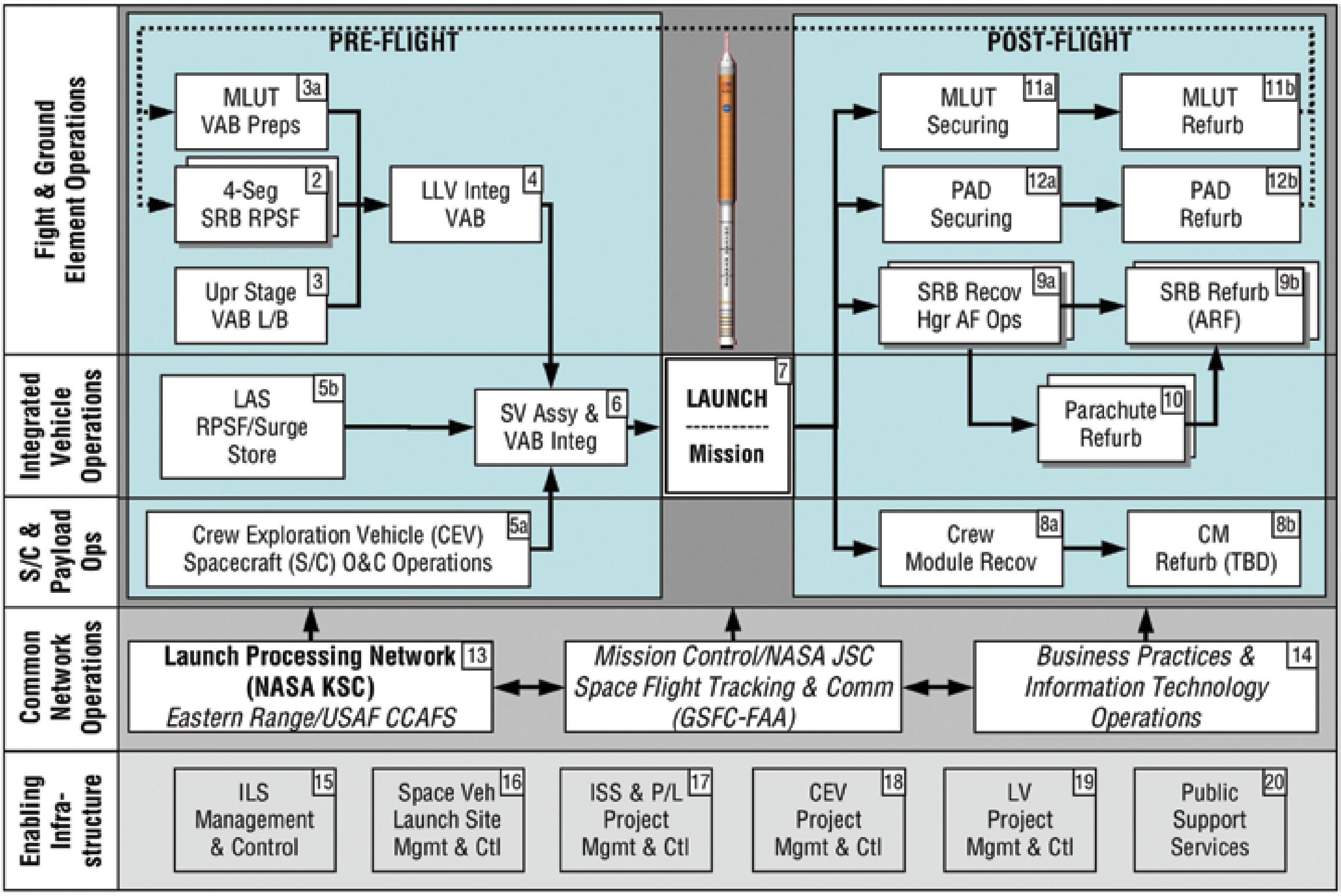


Figure 7-5. CEV/CLV Ground Operations Architecture

Reference Processing Flow for Crewed Flights

1. One of the converted Shuttle MLPs, now a MLUT, is positioned in a VAB Integration Cell (VAB High Bay).
2. A four-segment Solid Rocket Motor (SRM) arrives by rail at the Rotation Processing and Surge Facility (RPSF), along with the refurbished forward frustum, SRB aft skirt, and a new nozzle extension for aft assembly buildup.
3. The CLV upper stage arrives at the VAB Low Bay equipped with a pre-fired single SSME.
4. A single SRB is stacked on the MLUT, followed by the mating of the upper stage. The adapter/forward frustum area is also set up for any necessary purges. The upper stage is mated to a single SRB.

5a. The CEV, composed of a CM and a SM, arrives at KSC's Operations and Checkout (O&C) Building for assembly, testing, and spacecraft integration. The integrated spacecraft assembly is then prepared for transport to the VAB (assuming no toxic propellants or any commodities requiring hazardous SCAPE operations are required—if so, then the spacecraft assembly may have to go through another hazardous facility in KSC's Industrial Area).

5b. The LAS arrives at Complex 39 for temporary ordnance storage (RPSF) until needed for final CLV element mating in the VAB Integration Cell.

6. The space vehicle assembly and integration process mates the CEV spacecraft to the LV and the LAS to the CEV spacecraft to form the integrated CEV/CLV space vehicle. All launch preparations, short of final pad propellant loading and ordnance installation that cannot be performed in the VAB, are completed. Hazardous operations for toxic Reaction Control System (RCS) assembly/servicing (if required) could occur here with facility clear restrictions, but require a thorough hazard analysis to be performed. The CLV space vehicle is then transferred to Pad 39 (A or B).

7. Launch operations include the mating of the MLUT to pad propellant and gas systems (with all flight-to-ground mates having occurred in the VAB). Personnel access for final ordnance hook-ups and flight crew ingress also occurs at the Pad. The clean pad design approach minimizes the amount of work content that occurs at the Pad. Final propellant loading, flight crew ingress, and countdown lead to CLV departure.

8a. The CM is land-recovered (Edwards Air Force Base (EAFB) prime is reference) with two land contingencies and ocean-recovery contingencies for launch and reentry aborts. Any required CM safing for transport to the refurbishment site is also accomplished.

8b. CM refurbishment includes heat-shield removal and replacement, parachute system restoration, post-flight inspections and troubleshooting, and the return of the CM to a launch processing state compatible with spacecraft integration. The location for this function could be KSC's O&C facility or a local off-site facility.

9a. A single four-segment SRB is ocean-recovered and returned to Hangar AF at Cape Canaveral Air Force Station for wash-down and disassembly, as is done with Shuttle SRB recovery.

9b. Disassembled SRB components are refurbished in a similar fashion as the Space Shuttle SRBs. SRM segments are returned to Utah for remanufacturing, while the forward frustum and aft skirt assembly are sent to the Assembly/Remanufacturing Facility (ARF) near Complex 39.

10. SRB parachutes, and possibly the CEV recovery chutes, are sent to the Parachute Refurbishment Facility in KSC's Industrial Area.

11a. Following CLV departure, the MLUT undergoes safety inspections while preparations for post-launch ground crew access are provided.

11b. The MLUT is restored and reserviced in preparation for the next flight.

12a. Following CLV departure, the Pad undergoes safety inspections while preparations for post-launch ground crew access are provided.

12b. Pad systems (kept to a minimum in the clean pad design approach) are restored and propellant systems re-serviced in preparation for the next flight.

Reference LSAM/CaLV Processing Description

A reference processing flow for the lunar cargo launch is described below and follows the numbered elements in **Figure 7-6**.

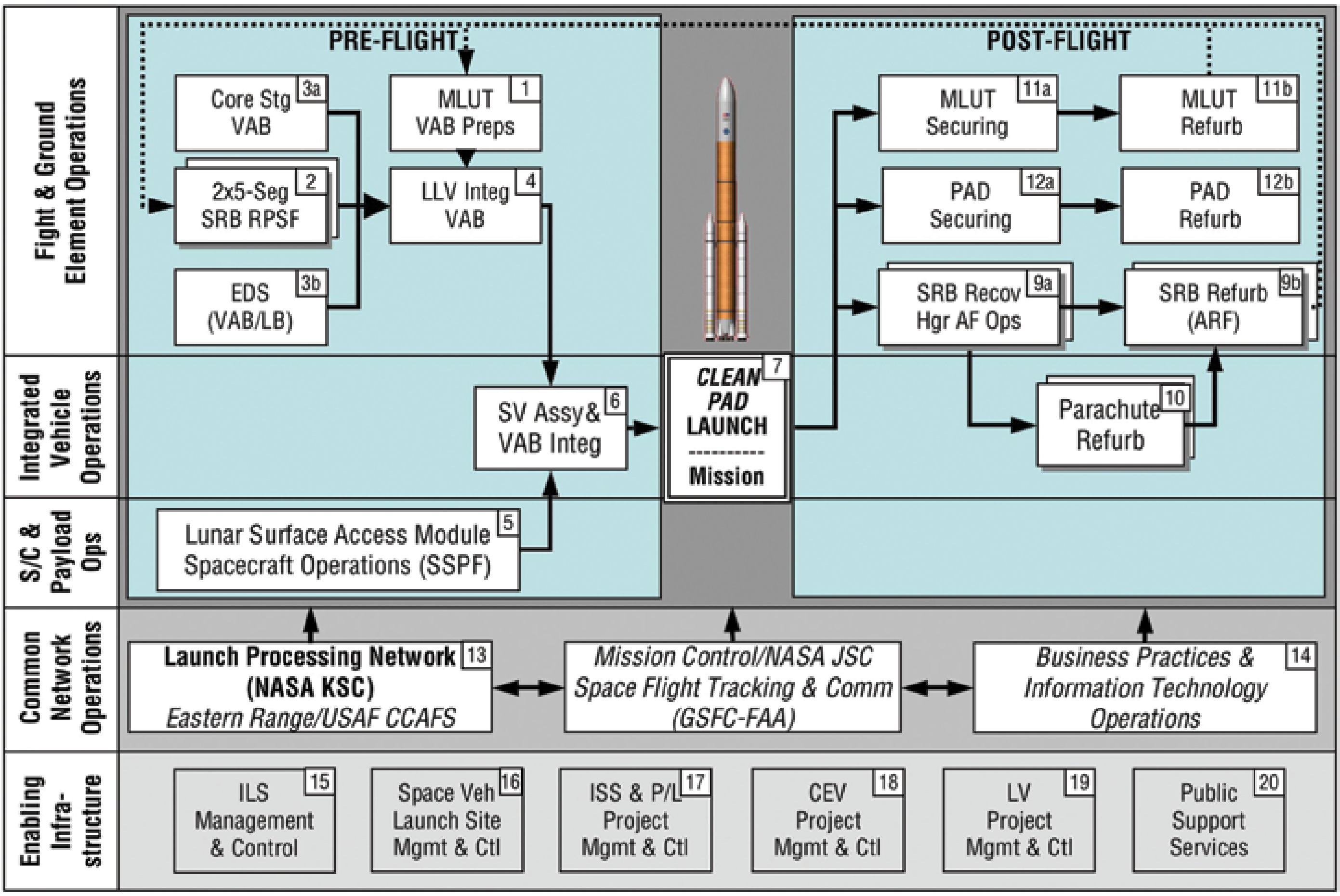


Figure 7-6. LSAM/CaLV Ground Operations Architecture

Reference Processing Flow for Lunar Cargo Launch

1. A newly designed MLUT is positioned in a VAB Integration Cell (VAB High Bays).
2. Two five-segment SRMs arrive at the RPSF along with refurbished SRB aft skirts, nozzles, and forward assemblies for segment rotation and buildup.

3a The core stage arrives in the VAB transfer aisle ready for mating to the MLUT. Five SSMEs arrive having already been built into stage and pre-fired and pre-tested at the factory. No stand-alone engine operations are assumed.

3b. The Earth Departure Stage (EDS) arrives at the VAB's Low Bay equipped with two J–2S multi-start engines. The stage is assumed to arrive with the engine and interstage adapter preassembled.

4. CaLV assembly and integration occurs in a VAB Integration Cell (or High Bay) with LV connections to ground services and integrated checks occurring in the VAB. The SRB stacking occurs and the core stage is mated to the MLUT, followed by the mating of

the EDS/interstage adapter assembly. The LV is mated to ground services through the MLUT in the VAB. The CaLV is assumed to require no hazardous SCAPE operations per the recommended ESAS requirements.

5. The LSAM arrives at KSC's Industrial Area for assembly, testing, and encapsulation in the CaLV forward shroud and is then prepared for transport to the VAB.
6. Space Vehicle Assembly and Integration mates an encapsulated shrouded LSAM spacecraft to the CaLV in the VAB integration cell. All launch preparations except final pad propellant loading and countdown occurs within the confines of the VAB (similar to many Saturn/Apollo tasks and Atlas V Operations).
7. Launch operations include the mating of the MLUT to pad propellant and gas systems through auto-couplers (all flight-to-ground mates having occurred in the VAB). Personnel access for final ordnance hook-ups and flight crew ingress also occur at the Pad. The clean pad design approach minimizes the amount of work content. Final propellant loading and countdown lead to the CaLV departure.
8. [There is no CM processing on the uncrewed CaLV configuration.]

9a. Two five-segment SRBs are ocean-recovered and returned to Hangar AF at Cape Canaveral Air Force Station for wash-down and disassembly.

9b. The disassembled SRB components are refurbished in a similar fashion as the Space Shuttle SRBs. The SRM segments are returned to Utah for remanufacturing, while the forward and aft skirt assemblies are sent to the ARF near Complex 39.

10. SRB parachutes are sent to the Parachute Refurbishment Facility in KSC's Industrial Area.

11a. Following CaLV departure, the MLUT undergoes safety inspections while preparations for post-launch ground crew access are provided.

11b. The MLUT is restored and re-serviced in preparation for the next flight.

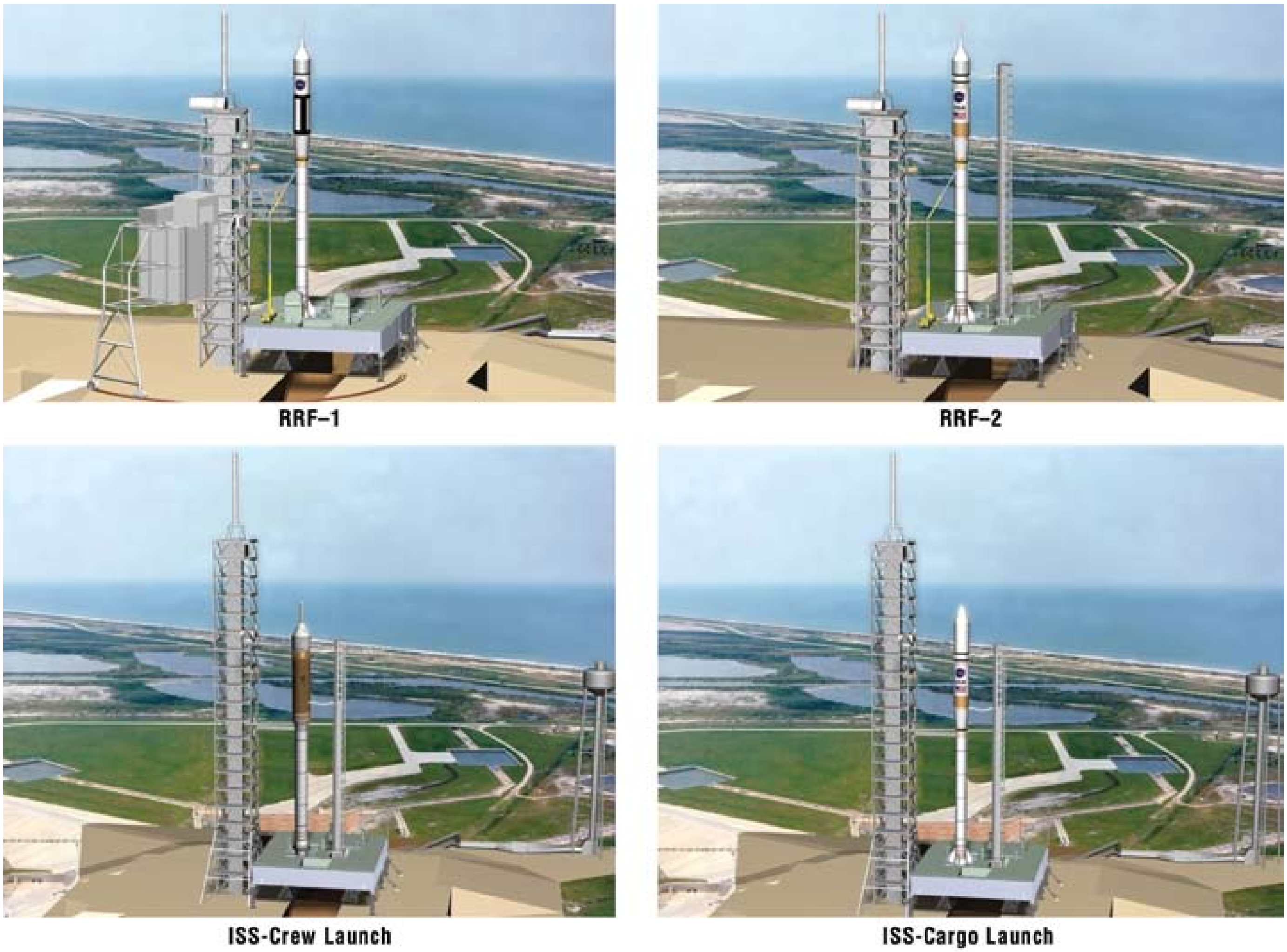
12a. Following CaLV departure, the Pad undergoes safety inspections while preparations for post-launch ground crew access are provided.

12b. Pad systems (kept to a minimum in the clean pad design approach) are restored and propellant systems reserviced in preparation for the next flight.

7.1.3 Launch Facility and Equipment Conversions

7.1.3.1 Development Schedule and Flight Test Manifest Assumptions

A preliminary analysis by the ESAS team provided a concept for conversion of the pads and MLPs to support the flight test program. Little or no modification is required for the mobile launcher for the first LC–39 flight (Risk Reduction Flight-1 (RRF–1)) because the flight configuration is largely composed of mass simulators and flown without crew. Therefore, assembly and integration can occur within the VAB, and pad personnel access can be confined to SRB S&A operations provided by mobile heavy equipment access. Little or no tear-down of the current pad (currently envisioned to be Pad B due to timing of Pad B long-term refurbishment) FSS and RSS are required to support this test flight. Some modifications are required for the mobile launcher for the second and third flights (Risk Reduction Flight-2 (RRF–2) and Risk Reduction Flight-3 (RRF–3) because servicing of the CLV upper stage is required. Assembly and integration occurs within the VAB and pad personnel access is still confined to SRB S&A operations provided by mobile heavy equipment access. Tear-down of the current pad RSS occurs after RRF–1 and after extensions to the FSS with associated personnel access provisions have been installed and activated. Additionally, the MLUT and associated systems are installed and routed throughout the MLUT internal structure while auto-couplers between the MLUT and pad are installed and certified for use. The final CEV/CLV space vehicle flight-ground system launch configuration accommodates both unmanned crew and cargo flights from Launch Complex 39. (see **Figure 7-7**.)


RRF–1

RRF–2

ISS-Crew Launch

ISS-Cargo Launch

Figure 7-7. Concept for CLV Pad Conversions through ISS Operation

A reference launch pad transition scenario envisions first launching the test and evaluation flights from Pad B (since it is the next pad scheduled to go off-line for long-term maintenance) with personnel access provided from the current FSS, most fluid and electrical services transferred to the converted Shuttle MLUT, and the RSS removed. This would be an interim step toward an LC–39 clean pad and would allow the current Space Shuttle to continue departures to the ISS from Pad A. For the lunar missions, Pad A would be "stripped down" to accept the new mobile launcher design, which would now have a more functional umbilical/access tower—similar in function to the Apollo-Saturn launcher. The method of crew emergency egress for such an approach has several design alternatives to be determined. This has been a classical launch site design issue for human space flight. Pad B could then be reconfigured to the new clean pad design at Pad A. In summary, the reference concept is to have two clean pads (39A and 39B) that can eventually accommodate both the CLV and CaLV configurations. It was not clear within the ESAS time frame for analyzing the 1.5-launch solution whether a universal mobile launcher design could accommodate both the CLV and CaLV. Cost estimates assumed that three converted Shuttle MLPs for the CLVs and two new mobile launchers for the CaLVs (a total of five mobile launchers) would be required for the program.

7.1.3.2 Spacecraft Processing Facility Conversions

7.1.3.2.1 CEV Architecture and Mission

The CEV architecture consists of three primary flight elements: CM, SM, and LAS. For spacecraft ground processing, the CM is assumed to be reusable, provided to the spacecraft assembly and integration area in a safe, nonhazardous condition that requires no propellant or ordnance handling in the processing facility.

The SM is assumed to be expendable and does not require hypergolic propellant servicing in the reference case. (Hazardous hypergolic propellant servicing was explored as a contingency during spacecraft integration prior to delivery for LV integration. The safety implications of this scenario, while accounted for in the cost estimates, will require a more thorough hazard and safety analysis). The LAS is expendable and arrives with solid fuel and is most likely stored in Complex 39 near the SRB segments. There is also the possibility of storing and mating as part of the Industrial Area spacecraft integration process, but this also requires a thorough safety and handling analysis.

The assumed Industrial Area processing analysis supports an annual launch rate of six CEVs with two crew missions, three pressurized cargo missions, and one unpressurized cargo mission per year on 2-month centers. It is also assumed that crew access is required at the pad.

7.1.3.2.2 CEV Infrastructure Assumptions

The CM and SM are assumed to be assembled, serviced, and integrated in a nonhazardous and/or hazardous facility, as required to support the CEV flight element design. Parallel clean work areas are required for processing a minimum of four CEV systems. Vacuum chamber testing may be required for CMs during flow.

The SM may require fueling in a hazardous facility. The LAS will be stored and processed in a hazardous ordnance facility. The worst case CEV spacecraft integration infrastructure assumes assembly of the CM, SM, and LAS performed in hazardous facilities. Integration with the CLV is performed in the VAB High Bay. Although crew access and emergency egress is required at the pad, propellant loading or servicing is not.

7.1.3.2.3 Operations and Checkout (O&C) Building Modifications and Development

The ESAS reference ground processing architecture assumes the O&C Building at KSC's Industrial Area is modified for CEV element processing and integration. (See **Figure 7-8**.) The final spacecraft element integration facility will be largely determined by the nature of the spacecraft subsystems and their hazardous processing requirements.

The O&C facility concept incorporates an open-floor design that is compatible with mobile Ground Support Equipment (GSE) to support CEV and/or other spacecraft hardware. The processing concept also incorporates standard services including compressed air, power, gases, vents, and instrumentation, and others as required to support the CEV flight systems. The concept also upgrades cranes to support the new program. It is envisioned that development of new common GSE for CEV processes and ISS interface testing will occur. This will also allow incorporation of state-of-the-art technology developments for fluids, avionics, and mechanical GSE. If required, the O&C vacuum environmental chambers will be verified for compatibility with program needs.

Figure 7-8. CEV Footprint in KSC's O&C Building

7.1.3.2.4 Space Station Processing Facility (SSPF) Modifications and Development

No facility modifications are planned for the initial CEV/CLV program. New GSE development for ISS interface testing may be performed. This SSPF is envisioned to continue support of the ISS program. Assets may transition over to support the LSAM as flight hardware and prototypes arrive at the launch site.

7.1.3.2.5 Vertical Processing Facility (VPF) Modifications and Development

The Vertical Processing Facility (VPF) is envisioned to be modified to support the CEV program if off-line hazardous integration and fueling of the CEV is performed in the Industrial Area (as opposed to launch pad servicing). This will require removal of platforms and other fixed GSE; incorporation of open floors compatible with mobile GSE to support CEV and/or other spacecraft; incorporation of standard services including compressed air, power, gases, vents, instrumentation and other services; accommodations made for CEV and/or other spacecraft fueling and ordnance installation; incorporation of technology development for fluids, avionics, and mechanical GSE; and development and acquisition of common GSE for CEV hazardous processing.

7.1.3.2.6 LSAM/SSPF Modifications and Development

Use of the SSPF is the ESAS reference concept for LSAM processing. The concept expands the work area from 8 to 12 footprints, includes a canister operations area and adds cranes and a new airlock, and develops new GSE for lunar spacecraft checkout and integration.

Since the LSAM is launched on a separate EDS that does not require a long-length shroud, it may be possible to use the SSPF or extend it to the east to perform final LSAM encapsulation in the payload fairing of a Heavy-Lift Vehicle (HLV). This would be sent as an integrated spacecraft package from KSC's Industrial Area to Launch Complex 39 for integration with the Heavy-Lift Launch Vehicle (HLLV). Precedence for this is found in the Skylab program.

7.1.3.3 CLV Facility/Equipment Conversions

7.1.3.3.1 CLV Architecture

The CLV architecture consists of a single four-segment Reusable Solid Rocket Booster (RSRB) first stage and a LOX/LH2 upper stage with a single SSME that is modified for altitude-start. The SRB is assumed to be reusable in the same manner as the Space Shuttle

Program. The CLV Upper Stage is expendable—with the SSME pre-fired, assembled, and checked-out prior to delivery and launch site acceptance. The launch rate is assumed to be six per year on 2-month centers.

7.1.3.3.2 CLV Infrastructure Assumptions

No additional processing areas, facilities, or GSE are assumed to be required for SRB operations. Some accommodation changes are expected due to the differences in forward frustum design. Launch Complex 39 RPSF operations are retained. Hangar AF SRB retrieval operations are retained and hazardous hydrazine de-servicing operations are maintained for the near-term only. The upper stage is assumed to require minimal processing in the VAB Low Bay where element receiving and acceptance and prestacking operations occur. Minimal infrastructure modifications are required. If toxic/hazardous RCS are employed on the CLV, it is assumed that those elements arrive preloaded. The hazardous, toxic propellant loading may be performed off-site and assembled onto the appropriate stage in the VAB (pending safety and hazard analysis). No hypergolic propellant loading system is envisioned in the VAB, on the mobile launcher, or at the pad—nor was such a system budgeted for in the ESAS ground architecture. It is also assumed that no clean room is required for upper stage processing or payload encapsulation at the VAB.

Three MLPs and two crawler-transporters are required to maintain the ISS tempo of six flights per year with periodic long-term restoration downtime required for these ground elements. The VAB is assumed to perform stacking and payload integration. For this capability, two VAB high bays (High Bays 1 and 3) are required for integration and are modified to support access and vehicle servicing and assembly requirements. The current Quantity Distance (QD) restriction of 16 SRB segments in the VAB applies, although ESAS has initiated a NASA reassessment of this requirement. The current 16-segment restriction is not believed to be a major restriction with the ESAS 1.5-launch solution for the two lunar mission per year rate. Two launch pads are assumed to be required, with crew access and emergency egress required at the pad. Main propellant loading is performed at Pad 39. No toxic or hazardous hypergolic loading or servicing is required at Pad 39. SCAPE operations are not envisioned in the ESAS reference concept at NASA's Complex 39.

The study assumes that an Apollo-like MSS is not necessary for the ESAS concepts if the nontoxic requirement is adhered to, or if toxic systems employed can avoid on-pad loading and servicing from the opposite side of the umbilical tower. The study also assumes that the CEV design and location of pyrotechnic arming locations can avoid the problems encountered in the Apollo Program by likewise locating pyrotechnic arming, or other functions requiring late manual access at the Pad, via crew access arms or from the base level of the mobile launcher (Moonport: A History of Apollo Launch Facilities and Operations, Chapter 13 "From Arming Tower to Mobile Service Structure," NASA SP-4204; Benson & Faherty, 1978).

An example of ground system design trades for modification of Launch Complex 39 is shown in **Table 7-1**. The objective of the concept trades is to determine how to accommodate fluid and propellant services and how best to provide personnel access.

	Design Options					'Goals'
Requirements	**Mod FSS**	**Mod MLP**	**New MLP**	**Hybrid**	**Hybrid**	**Clean Pad**
Lightning Protection	FSS	Faraday	Faraday	Faraday	Faraday	LUT
Emergency egress	Slidewire	Track	Chute	Slidewire	Chute	Safe/Low Ops
Crew access OAA	FSS	LUT	LUT	FSS	FSS	LUT
LOX/LH2 servicing	FSS	LUT	LUT	LUT	LUT	LUT
SRB S&A Access	FSS	LUT	LUT	FSS	LUT	LUT
MLP Structure	STS	Mod STS	New	Mod STS	New	New
VAB Changes	Low	High	High	Low	Medium	-
Schedule Availability	Late	Late	Late	RRF-1	Con-1	Con-1
Cost	Medium	Medium	Medium	High	Medium	Affordable

Table 7-1. Example Pad/MLP/VAB System Trades

The current Space Shuttle configuration of Pad 39 provides fixed services at the launch pad, with a mobile platform carrying the space vehicle to the pad to connect up to those services. As previously mentioned in the clean pad approach, both services and access can be attached to the mobile platform, as was done with the Apollo-Saturn configuration.

The ESAS reference is currently a hybrid approach, where the services are provided on a MLUT with minimal personnel access at the pad provided through a modification and extension of the current Space Shuttle FSS. The Shuttle pad current RSS is no longer required because late-payload assembly and integration to a side-mounted space vehicle will not occur at the pad, and hypergolic servicing of side-mounted RCS will not be required.

Elevated vehicle personnel access at the pad is assumed for SRB Safe and Arm (S&A) operations, as well as for late flight crew stowage, flight crew ingress, and emergency flight crew egress. Ground services to the CEV/CLV space vehicle include hardwire command and data paths, electrical power, nitrogen purging of the aft skirt (if hydrazine is maintained on the SRB Thrust Vector Control (TVC) system), cryogenic loading, upper stage and interstage conditioning and purging, and spacecraft propellant and gas system servicing. Some of the services may be performed in a local/manual mode in the VAB or in a remote/manual or remote/automated mode from a control center.

Lightning protection for the space vehicle will also be accommodated at the pad. Several alternative design concepts for this function are available, including a tall lightning mast mounted on the LUT or a permanently pad-mounted system of "Faraday Cage" towers.

Each of these trades must be integrated to complete the ground architecture, including the VAB, mobile launcher, and pad system designs. The availability of Space Shuttle MLPs, pads, and VAB Integration Cells (high bays) are factored into the initial ISS CEV/CLV space vehicle ground support architecture and related costs.

In order to perform the space vehicle integration for the CEV/CLV, the VAB's extensible platforms will require modification. These large facilities translate in and out to provide access for personnel to perform on-vehicle assembly, any local-manual flight element servicing operations, and final closeout activities prior to space vehicle rollout.

The ESAS team provided a conceptual design for the redesign of these VAB extensible access platforms as shown in **Figure 7-9**.

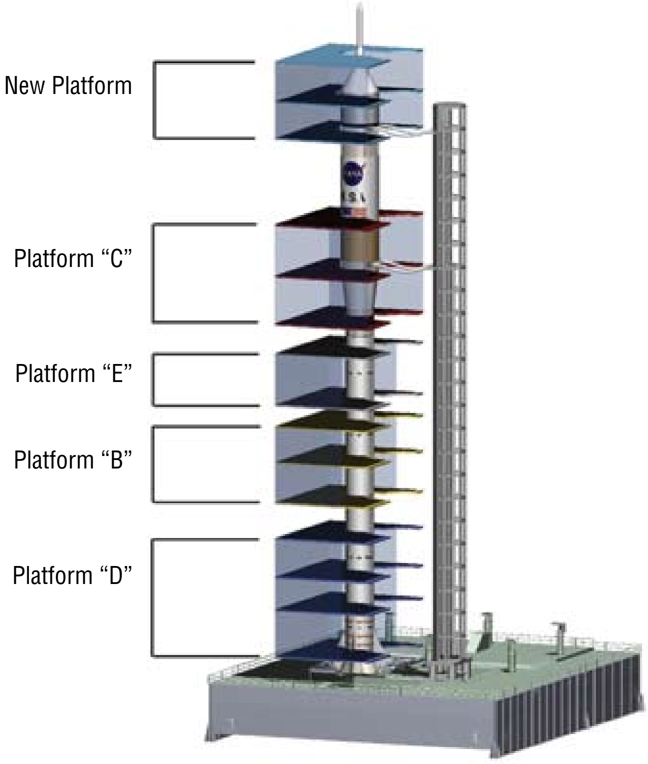


Figure 7-9. Vehicle Assembly Building High Bay Extensible Platform Concept

7.1.3.4 CaLV Facility/Equipment Conversions

7.1.3.4.1 CaLV Architecture

The CaLV architecture consists of two five-segment SRBs, a liquid core stage with five SSMEs, and an EDS with two J–2S multi-start engines. The SRBs are assumed to be reusable in the same manner as the Space Shuttle Program and the CLV. The launch rate is assumed to be two CaLV's per year on 6-month centers.

7.1.3.4.2 CaLV Infrastructure Assumptions

No additional processing areas, facilities, or GSE are assumed to be required for five-segment SRB operations. Some minor changes are expected due to the five-segment, versus four-segment, configuration. Launch Complex 39 RPSF operations are retained. Hangar AF SRB retrieval operations are retained, and hazardous hydrazine deservicing operations are maintained for the near-term only. The EDS is assumed to require minimal processing in the VAB Low Bay where element receiving and acceptance and prestacking operations occur. Minimal infrastructure modifications are required. No toxic/hazardous RCS are assumed to be employed on the CaLV. The hazardous, toxic propellant loading may be performed off-site and assembled onto the appropriate stage in the VAB (pending safety and hazard analysis). No hypergolic propellant loading system is envisioned in the VAB, on the mobile launcher, or at the pad. Nor was such a system budgeted for in the ESAS ground architecture. It is also assumed that no clean room is required for EDS processing or payload encapsulation at the VAB.

Two new MLUTs and two new crawler-transporters are required to maintain a lunar campaign tempo of two flights per year with periodic long-term restoration downtime required for these ground elements. The VAB is assumed to perform stacking and encapsulated payload integration. For this capability, one VAB high bay is required for integration and is modified to support access and vehicle servicing and assembly requirements. The current QD restriction of 16 SRB segments in the VAB applies, although ESAS has initiated a NASA reassessment of this requirement. The current 16-segment restriction is not believed to be a major restriction, even with one five-segment pair for the CaLV and a single-four segment CLV in stacking to support the two lunar mission-per-year rate. Two CLV/CaLV launch pads (39-A and 39-B) are assumed to be required. Main propellant loading is performed at Pad 39.

In order to accommodate the space vehicle integration for the LSAM/CaLV, one of the VAB's extensible platforms will require modification. These large facilities translate in and out to provide access for personnel to perform on-vehicle assembly, any local-manual flight element servicing operations, and final closeout activities prior to space vehicle rollout.

7.1.4 Cost Estimation Approach

For the cost estimation approach and results, reference **Section 12**, **Cost**.

7.1.5 Special Topics

7.1.5.1 Design Process Controls to Manage Inherent Complexity and Dependability

The ESAS team, working under a tight architecture definition time constraint, diligently worked to alleviate the level of ground operations work. This was done by searching for space vehicle configurations with the least number of practical stages, the fewest number of engines, and the fewest number of different engines where practical. During the ESAS effort, specific design characteristics, such as the toxicity of fluids, the number of different fluids, and the number of separate subsystems were used by the team. (Reference **Appendix 7C**, **ESAS Operability Drivers**.)

In order to contain the ground operations costs (both development and recurring operations and support), it is vital that these design characteristics be quantified and baselined at the start of the program. These parameters should then be managed through a tracking system that includes a means of surfacing deviations from the baseline to high-level program management and NASA independent program assessment. If no constraints other than on weight and performance are applied to the design process, the ground operations costs will be difficult to control.

7.1.5.2 Integrated Logistics Support and Affordable Supply Chain

For the integrated logistics support and affordable supply chain analysis, reference **Section 12**, **Cost**.

7.1.5.3 Reuse of SRB and CM

7.1.5.3.1 SRB Reuse Opportunities

The ESAS effort determined that the reuse of the SRBs is more economically viable than continually producing the segments, aft skirts, etc. (Reference **Section 12**, **Cost**). The ground operations processes for SRB reuse are envisioned to follow the same process and have the same infrastructure as that of the Space Shuttle program. This section describes some architectural options for consideration to improve Life Cycle Cost (LCC) and the throughput performance capability.

The SRB's TVC system involves two major subsystems: a 3,000-psi hydraulic actuation subsystem and a toxic hydrazine Hydraulic Power Unit (HPU) that converts the stored chemical energy in the hydrazine monopropellant to mechanical shaft power for a hydraulic pump by means of a catalytic bed that generates hot-gas exhaust expanded through a turbine drive. (See **Figure 7-10**.)

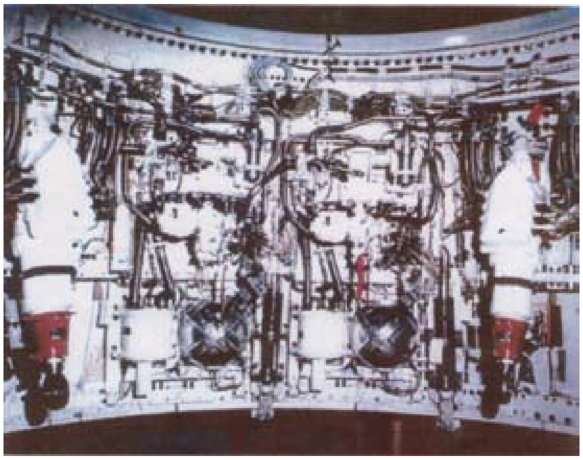


Figure 7-10. SRB Aft Skirt Thrust Vector Control Installation

The toxic hydrazine loaded into the SRB aft skirts drives expensive, hazardous, and time-consuming SCAPE operations in a number of areas across the nation. A dedicated aft skirt safing and disassembly facility is required at Cape Canaveral's Hangar AF SRB Disassembly Area. After the nearly year-long process of remanufacturing the aft skirt components and aft skirt resurfacing, inspections, and checks at NASA MSFC's ARF located within the KSC property, the completed aft skirt is transferred to another dedicated facility to hot-fire test the hydrazine-powered assembly, where more SCAPE operations occur. The system is then drained of the toxic hydrazine, safed, secured, and prepared for delivery to KSC's RPSF for SRB aft booster assembly. Final hydrazine loading of the SRB TVC system occurs at the launch pad just prior to launch. As with all SCAPE operations, this is a hazardous operation under local manual control with remote monitoring of the operations with fire and medical rescue support available. Hazardous operations are also repeated at the manufacturing site for motor firings involving the TVC that may occur. For a more detailed description of the process, reference **Appendix 7D**, **Toxic, Hazardous Operations Impacts**.

Some alternatives should be explored to eliminate the SCAPE operations hazards. Much preliminary engineering has already been accomplished on these alternatives. For example, NASA conducted a multi-center Electric Actuation Technology Bridging Study during the early 1990s that looked at all-electric solutions involving replacing the distributed hydraulic actuators with either Electro-Mechanical Actuators (EMAs) or battery-powered self-contained Electro-Hydrostatic Actuators (EHAs). Replacement of the similar hydrazine-powered APU on the Orbiter with an electric actuator and the SRB HPU with a high-pressure cold-gas blow-down system was also engineered in the late 1990s. Both of these nontoxic APU/HPU solutions should be resurrected for consideration in the CLV, and the self-contained hydraulic actuator should be considered for the five-segment solid qualification program.

7.1.5.3.2 Crew Module Reuse Considerations

Economic analysis by the ESAS team indicates that NASA baseline reuse of the CM. (Reference **Section 12**, **Cost**.) NASA KSC experience in reuse of space flight hardware shows that prediction of unplanned work levels, resulting direct costs and infrastructure support costs, and prediction of reuse turnaround times are very difficult and require broad uncertainty bands around such predictions. The reality is that NASA will not know the true outcome until full-scale, fully functional hardware systems, subsystems, and parts go through the ascent, on-orbit, entry, landing and recovery, and ground remanufacturing environments.

During the design phase, it is important for the end-items to be specified with design life parameters that are appropriate for the above environments and for the individual components, rather than assuming a design life commensurate with the airframe (as was done with the Space Shuttle). When allocating the design life, the amount of ground power-on time, power-on/off cycles, tank/system pressurization cycles, and so forth are highly important in containing the level of unplanned work (or even planned work in the case of limited life items).

A reusable CM needs known structural margins designed in and verified before delivery to avoid intrusive and time-consuming structural inspections. This means that Structural Test Articles (STAs) should be loaded and tested to destruction, as is done with reusable aerospace vehicles. The key to eliminating unwanted tests and inspections is to gain engineering confidence by investing in such tests and test articles. This approach has been assumed in the ESAS cost estimation results (**Section 12**, **Cost**).

Additionally, the CEV program should invest early in a thorough, first-class Maintenance Engineering Analysis (MEA) that is factored into the overall system and subsystem designs and again into the end-item specification process—with a design certification and buy-off process before delivery. In order to meet the first CEV deliveries, there will be a tendency for the manufacturer to push for completion of final assembly and other “minor” manufacturing tasks that tend to accumulate at the launch site. Experience has proven during human space flight programs (particularly the Shuttle Orbiter) that this tendency destroys launch site flow planning and creates net wasted time and effort. Adherence to a clear contractual final delivery plan is a must to meet the CEV/CLV test and evaluation objectives and schedules.

Provided below is a quick overview of the type of work that may be required for CM refurbishment. The work tasks below assume the ESAS reference CEV with accommodations for up to a crew of six. It further assumes that the CM has already been recovered (land or ocean) and arrives at a refurbishment/remanufacturing facility.

Top-level refurbishment categories may include the following:

- Facility/Equipment Preps and Setups for CM Refurbishment;
- CM Handling and Positioning, Connection to Services, Gaining Access, and Protection;
- CM Post-Flight Safing;
- CM Post-Flight Inspections and Servicing;
- CM De-servicing;
- CM Unplanned Troubleshooting and Repair;
- CM Modifications and Special Tests;
- CM Reconfiguration;

- Closeout for CM Delivery/Turnover; and
- CM Refurbishment Facility and Equipment Periodic Maintenance.

A more detailed list of tasks is shown in **Table 7-2**.

Table 7-2.
CM Refurbishment Work Tasks

CM Refurbishment and Recertification for Launch Processing	
Facility Preps for CM Refurbishment	Functional verification of ground systems prior to vehicle arrival
	Servicing and staging of ground systems prior to vehicle arrival
	Contamination control preps and setups
CM Handling and Positioning, Connection to Services, Gaining Access, and Protection	CM transport and alignment in refurbishing stands
	Ground access kit positioning
	Connection to facility electrical, data, fluid, and gas services
	Establish protective enclosures and install/remove flight vehicle protective covers
	Removal of external flight equipment covers/panels to gain access
	Open CM hatches
CM Post-Flight Safing	Hazardous fluid and pyro/ordnance safing
	Establish CM purges for personnel/CM safety
CM Systems Deservicing	Landing bag system rework
	Parachute recovery system rework
	Other CM mechanical systems recalibration, lubrications, etc.
	Routine replacement of environmental control filters and window cavity purge desiccants, etc.
	Flight crew systems deservicing
	Passive thermal protection routine replacement (known limited life)
	Thermal Protection System (TPS) seal replacements as required
	Fluid drain and deservicing
	Application of blanket pressures for transport and delivery, if required
	Navigation and instrumentation component servicing and calibrations
	Routine replacement of expendable and limited life CM components
	Application of CM electrical power and avionics systems health monitoring
CM Post-Flight Inspections and Checkout	CM structural integrity inspections and mechanism functional verifications
	Propellant, fluids, and gas system leak checks, functionals, and inspections
	CM powerup, switch lists, functional checks, and onboard software updates and checks
CM Mission Reconfiguration	Reconfigure TPS and chutes
	Remove unique mechanisms (e.g., seats, cargo restraints, etc.) from previous mission/Install unique mechanisms for upcoming mission and recertify for delivery
	CM pressurized cabin locker/stowage area, displays and controls, etc., reconfiguring, cleaning, and recertification for delivery

Table 7-2. CM Refurbishment Work Tasks (Continued)

CM Refurbishment and Recertification for Launch Processing	
CM Unplanned Troubleshooting and Repair	CM Line Replaceable Unit (LRU) troubleshooting, replacement, disposition of failed and suspected failed components
	Troubleshooting and repair of leaks
	Fluid/pneumatic system decontamination and cleaning
	Electrical cable and connector troubleshooting, retest, and repair
	Unplanned troubleshooting or replacement of TPS hardware (not routine replacements)
	Unplanned structural repair/refurbishment
	Repair of ducts, tubes, hoses, mechanisms, and thermal/pressure seals
	Troubleshooting and repair of ground support equipment
CM Modifications and Special Tests	Flight equipment modifications/upgrades and mandatory Material and Process (M&P) changes
	Special tests, fleet system, and component cannibalizations
Closeout for CM Delivery and/or Further Spacecraft Integration	Removal of ground services, umbilicals, and personnel access equipment
	CM system closeouts for SM/spacecraft integration
	Final CM cleaning and preps for delivery
CM Refurbishing Facility and Equipment Periodic Maintenance	Interval maintenance of CM refurbishment equipment
	CM refurbishment facility and system modifications and M&P changes

Segregation of the normal CM preflight preparations (i.e., CEV spacecraft assembly and integration and servicing) from the CM refurbishment function should be considered. To better ensure that design corrective action occurs for unplanned, nuisance, and high-maintenance surfaces during the CEV test and evaluation period, it is recommended that the design center initially take responsibility for the refurbishment process similar to the way NASA Marchall Space Flight Center (MSFC) controls the SRB process locally in the ARF at the Cape. That function, however, should be collocated with launch operations resources. Once refurbishment operations and design modifications to improve component dependability have stabilized, a smooth transition of the refurbishment function to the launch operations center can occur. It is also recommended to provide the CM development contractor with incentives during the CEV acquisition process to activate an aggressive maintainability-by-design corrective action process that demonstrates to NASA the maximum benefit that can be obtained by CM reuse by the end of the flight test program.

7.1.5.4 Command and Control (C&C) Concepts

7.1.5.4.1 Background

Unique stovepipe Command and Control (C&C) systems are traditionally built for the various ground operational elements within a program. This approach leads to the proliferation of independent systems with duplicative functionality, logistics requirements, and multiple sustaining engineering organizations. Development, operations, and maintenance of these individual systems both complicate operations and result in high LCCs.

7.1.5.4.2 Goals and Objectives

The primary goal of the ground C&C concept is to take advantage of the commonality that exists across ground C&C systems and to reduce program cost of ownership through large-scale reuse of software across Constellation ground operational systems.

7.1.5.4.3 Technical Approach

Software and hardware product lines are rapidly emerging in the commercial marketplace as viable and important development paradigms that allow companies to realize order-of-magnitude improvements in time-to-market, cost, productivity, quality, and other business drivers. A software and hardware product line is a set of software-intensive systems that share a common, managed set of features that satisfy the mission needs and are developed from a common set of core assets.

Constellation C&C Product Line

The technical approach is based on the application of the product line strategy to program ground operations C&C systems. Rather than stovepipe C&C systems, the approach focuses on developing a family of related systems. The Constellation C&C product line is intended to provide the foundation for the system family capable of supporting vehicle/spacecraft integration, launch site processing, and mission operations.

The context of the product line is characterized at a high level in **Figure 7-11**, where the external interfaces are described in the green boxes, operations are described in the blue boxes, and the product line systems are described in the circle. The connecting lines represent the major external interfaces for the product line systems. The product line systems provide those control and monitoring capabilities for the LVs, spacecraft, and GSE necessary to support program operational needs. The capabilities of the product line systems include services for real-time data visualization, data processing, data archival and retrieval/analysis, end-item simulation, configuration, and mission customization. Data products exported and/or ingested from external data repositories and business information such as email and process documents are exchanged with the Management Information System (MIS) infrastructure.

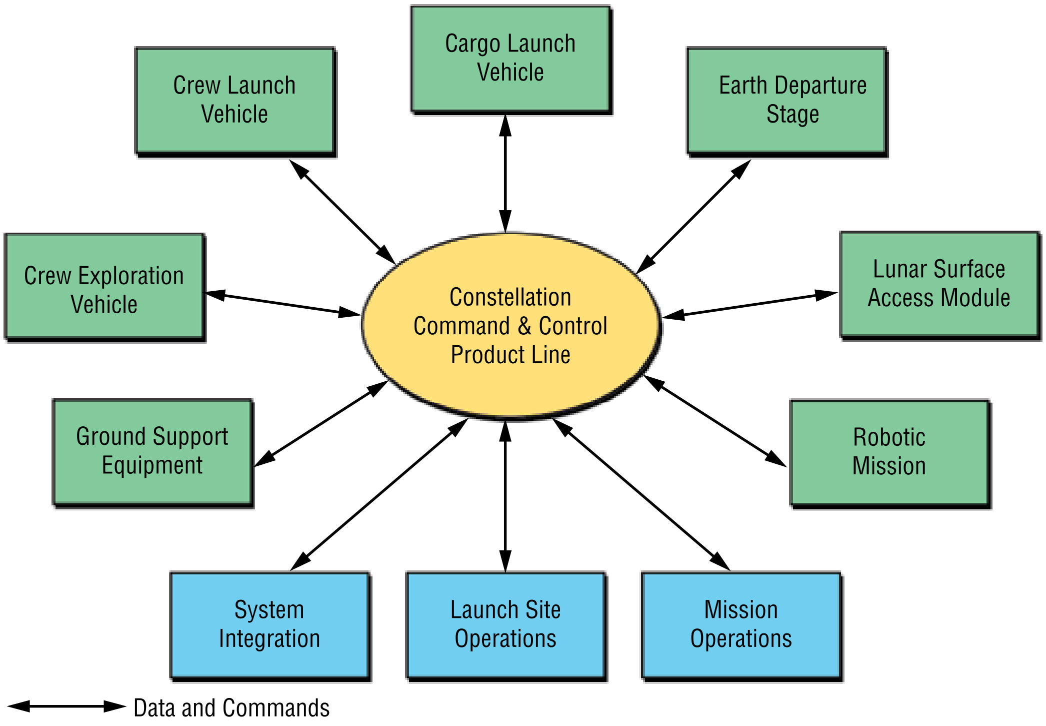


Figure 7-11. Constellation C&C Product Line Systems

System Context

The context of a product line system is characterized at a high level in **Figure 7-12**, where the product line services are represented in the circle and site/mission specific elements necessary to support operations are represented interfacing to the services.

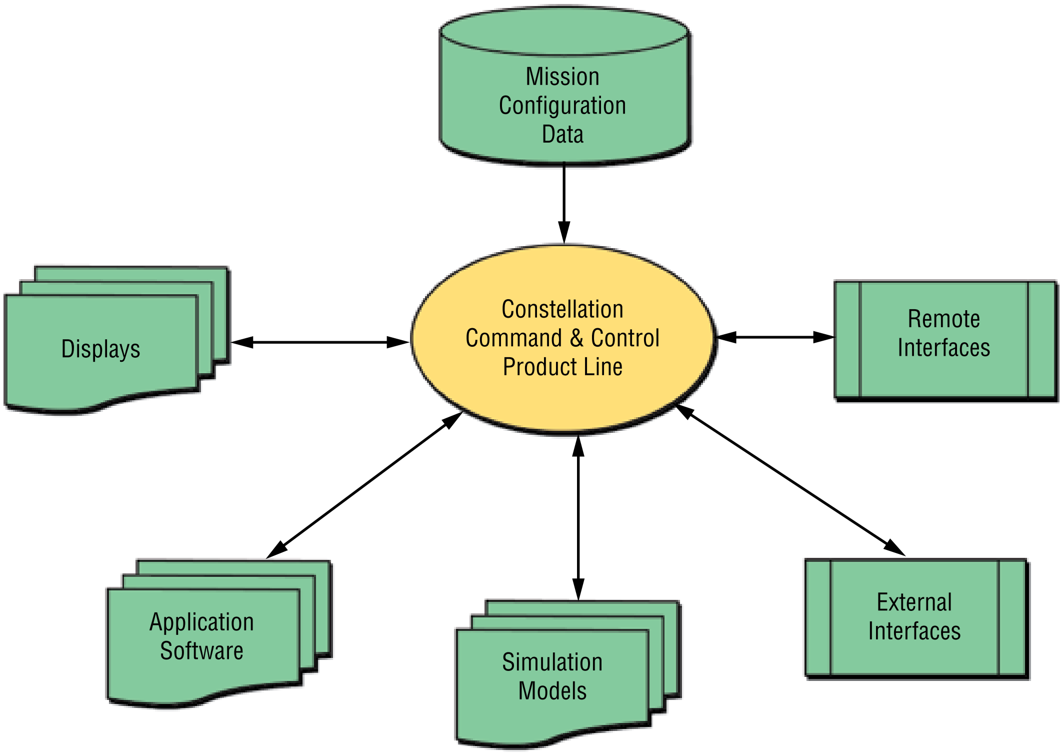


Figure 7-12. Product Line System Context

The product line services provide those capabilities common across Constellation C&C systems. These services include the following capabilities:

- C&C system configuration for operations;
- Real-time control and infrastructure monitoring;
- Web-based access for remote users;
- Data processing and command routing;
- Archival, retrieval, and support of the analysis tools;
- System management and redundancy; and
- Simulation infrastructure for external interfaces simulations.

Site and mission-specific functionality provides those capabilities unique to a specific operational activity. These services include the following capabilities:

- Mission Configuration Data: The repository of all information required to configure the ground systems to support operations;
- Displays and Applications: The system-unique (i.e., CEV, CLV, CaLV, EDS, and LSAM) capabilities required for functional verification, system integration, ground processing, troubleshooting, servicing, and launch processing. Also included are those capabilities required to support the planning and scheduling of communications, resource, and mission activities;
- Simulation Models: The system-unique behavior models required for software certification and training (launch team, mission operations team, and crew);
- External Interface: The interfaces necessary to collect and distribute vehicle, spacecraft, and GSE measurement data and initiate effecter and/or state commands; and
- Remote Interfaces: The interfaces necessary for remote users to monitor operational activities.

7.2 Flight Operations

7.2.1 Exploration Mission Operations

In order to perform a comprehensive cost, schedule, and performance analysis as part of this study, the following basic assumptions, guidelines, and ground rules were used to relate to all aspects of exploration mission operations. These are discussed in the following order within this section:

- Scope of mission operations,
- Mission design and activity planning,
- Crew and flight controller training,
- Flight mission execution and support,
- Mission support segment infrastructure,
- Communications and tracking networks, and
- Mission operations infrastructure transition and competency retention.

7.2.1.1 Scope of Mission Operations

Successful human space flight operations are founded on the program management, operations, and sustaining engineering "triad," providing a robust system of checks and balances in the execution of each human mission. This principal is fundamentally true regardless of program scale or nationality. Although small-scale programs, in which personnel may play multiple roles, quite often blur the lines of distinction between the three elements, the lines of distinction are still functionally present. **Table 7-3** summarizes the functional responsibilities by phase of mission operations development and summarizes the function of each group as it relates to the essential flight planning, training, and execution process.

The roles and responsibilities of each element of the triad comprise the total definition of "mission operations" as it pertains to cost of operations. Management provides program requirements to the operations community and sets priorities for each flight or mission. Operations provides the facilities, tools, training, and flight control personnel to plan and execute real-time operations of the assigned mission per the program's requirements. Engineering provides the spacecraft design expertise to validate that operational plans and procedures fall within the limits and capabilities of the flight vehicle.

Differences between human spaceflight and other spacecraft operations are rooted in:

- The differences in scale with respect to complexity of in-space elements;
- The mitigation of risk to the human element as well as to the facility itself; and
- The scale of multinational relationships where international partners are involved.

Table 7-3. Program Management, Operations and Engineering Sustaining "Triad"

	Management	Operations	Engineering
Plan	• Provide prioritized requirements for each increment/expedition • Provide definition of logistics requirements	• Plan and coordinate each increment/expedition • Develop crew procedures • Develop detailed EVA tasks • Develop detailed robotics tasks	• Define vehicle constraints on operations • Validate operations plans based on vehicle design limitations • Identify changes to logistics and maintenance requirements • Validate procedures based on vehicle design
Train	• Identify mission-unique tasks to be trained • Assembly • Maintenance • Utilization	• Development of training capability and curriculum • Train flight controllers and flight crews on vehicle systems operations • Train all EVA and robotics operations • Provide flight crews language training • Train flight crews and science investigators on science experiment operation	• Support development of new training content
Fly	• Provide management oversight of daily operations • Provide requirements-related and top-level tradeoff decision-making	• Real-time decision-making • Command and control all human elements of the exploration architecture • Coordinate among multiple control centers and numerous worksites to plan and execute daily plans • Build and maintain facilities to interface with all elements of the exploration architecture	• Lead resolution of in-flight anomalies with flight systems • Validate (as required) short-term plans based on vehicle design limitations • Build and maintain flight software and onboard crew displays

While there have been major technological advances in the 40-plus years of human space flight related to the tools of the trade, the fundamental functions necessary to plan, train, and fly a human space flight mission have not changed. Barring major improvements in the technologies of the vehicles involved well beyond the capabilities reasonably attainable through the year 2025, this fundamental process should hold true for many years to come. The following summarizes the primary functional responsibilities in the "plan-train-fly" sequence of activities:

7.2.1.1.1 Plan – Mission Design and Activity

- System design phase support by advocating for operability;
- Trajectory analysis and design;
- Flight planning and crew timeline scheduling;
- Systems and integrated procedures development;
- Flight and ground segment software development;
- C&C systems development and reconfiguration; and
- Operations procedures development and maintenance.

7.2.1.1.2 Train – Crew and Flight Controller

- Provide crew and flight controller training at the major training facilities;
- Develop simulators, mockups, and part task trainers;
- Define lesson and facility development; and
- Support certification of critical personnel.

7.2.1.1.3 Fly – Mission Execution

- Provide flight directors, flight controllers, and a Mission Control Center (MCC) operations support team;
- Provide an MCC, integrated planning system, and communications and tracking network; and
- Perform MCC functions during flight execution:
  - Crew communications and health monitoring,
  - Anomaly response and resolution,
  - Ascent/entry support and abort prediction,
  - Mission timeline planning and modification,
  - Spacecraft housekeeping, command, and control,
  - Engineering data gathering and archiving, and
  - Trajectory and rendezvous planning and execution.

7.2.1.2 "Plan" – Mission Design and Activity Planning

The keys to success in human space flight are found in meticulous and comprehensive mission design and activity planning. It is in this phase that every detail of mission execution is scrutinized, studied, and negotiated among the operational stakeholders. Facilities must be designed and implemented to train the operators (crew and flight controllers) and support mission execution through control center systems and their supporting communications networks. Mission planning occurs under the overall guidance and direction of the flight director, who will conduct the real-time mission. Specialists from each discipline are assigned to perform and support the following technical areas:

- Ground segment platform development
  - Flight controller workstation,
  - Facility design and development,
  - Command, control, and communications, and
  - Information Technology (IT).
- Technical data acquisition for spacecraft systems
  - Command and telemetry,
  - Software/firmware logic,
  - Instrumentation, and
  - Nominal/off-nominal performance.

- Intradiscipline operating concepts formulation
  - Crew displays and controls,
  - Ground segment displays and controls,
  - Flight rules governing responses to off-nominal system performance and contingency situations,
  - Crew and ground segment procedures for C&C,
  - Nominal operating procedures,
  - Off-nominal procedures, and
  - Backup/contingency procedures.
- Interdiscipline operating concepts formulation
  - Team interaction protocols;
    - Flight controller to program,
    - Flight controller to engineering, and
    - Flight controller to partner control center.
  - Flight rules governing integrated responses to multidiscipline contingency situations; and
  - Crew and ground segment integrated procedures for C&C.
- Participation in testing of flight elements
  - Flight segment stand-alone testing of flight element;
  - Flight segment element-to-element testing; and
  - Closed-loop testing with ground segment.
- Flight planning and production
  - Mission planning and design,
  - Trajectory design,
  - Crew activity planning,
  - Ground-controlled activity planning,
  - Flight software reconfiguration (flight-specific command and telemetry definitions), and
  - Command and telemetry format definition.

The integrated team works with the program elements to provide definition to these areas and develop detailed plans, procedures, and mission rules. The flight director uses a common forum known as “flight techniques” in the integration of these activities.

The operations community must be involved in the Design, Development, Test and Evaluation (DDT&E) of all exploration system space flight elements. Operations personnel (flight crew and controllers) should play an active role during the design process to ensure that systems designs meet operational objectives. The operations personnel provide insight to program management to ensure that the design meets operational needs. Interaction between the development and operations personnel will occur throughout the design process and will come to a focus during significant design reviews. Operations personnel should also participate in requirements verification processes. As preliminary operational procedures are developed, they should be validated on the hardware by operations personnel and flight crew. Working relationships developed between the operations and engineering personnel will carry over into the mission execution phase.

7.2.1.3 “Train” – Crew and Flight Controller Training

As the mission planning phase nears completion, the integrated team of crew and flight controllers applies the results in a set of plans and operational products (i.e., procedures and mission rules) that can then allow training specialists to develop both generic (i.e., all-mission) and flight-specific training. The following summarizes the scope of this area of emphasis.

Training facilities/platforms development includes part task trainers, mock-ups, Virtual Reality (VR) trainers, dynamic simulators, engineering simulators, and integrated mission simulators.

Training content development requires significant progress in systems operations concepts and product development. This development also examines the roles of crew versus ground personnel in systems operation.

Crew training consists of classroom instruction, workbooks, part task trainers, and Computer-Based Training (CBT). This training may be conducted as stand-alone (intracrew coordination, drill systems knowledge, and skills) or integrated with the ground segment.

Flight controllers training consists of classroom instruction, workbooks, part task trainers, and CBT. This training includes part task trainers (drill systems knowledge, skills, and expertise), integrated simulations (team coordination and console management), and certification.

7.2.1.4 “Fly” – Mission Execution

Exploration missions will have multiple transit and orbital vehicles and operating surface installations, with several vehicles and installations operating simultaneously. Human and robotic exploration resources will have to be simultaneously managed, while international and commercial resources are likely to require simultaneous management as well. As a result, the exploration program will have the challenge of defining an efficient and appropriate C&C architecture.

7.2.1.4.1 Guiding Principles

The ESAS team envisions a set of guiding control principles for exploration missions. Crewed vehicles should nominally be controlled by the crew independent of Earth and be capable of being under Earth control independent of the crew. Empty and support vehicles can be controlled by Earth or by crewed vehicles in proximity. Robotic vehicles can be controlled by Earth or by crewed vehicles as appropriate for their function. For example, robotic orbiting assets would be primarily controlled from Earth, and teleoperated rovers would be controlled by crews when crews are in proximity. All vehicles will be self-sustaining without Earth or crew intervention between critical events for up to 2 days for lunar missions or 2 weeks for Mars missions, including in the event of single failures of any system(s). Vehicles will maintain command ability after such events. All vehicles will operate autonomously during critical events.

7.2.1.4.2 Command and Control

One central authority should direct all assets in accomplishing the mission. While control may be distributed to leverage existing operational capability and infrastructure, decision-making authority must be centralized. While encouragement of international participation is an acknowledged Level 0 requirement, operational C&C of the crewed elements of human exploration missions will remain NASA’s responsibility.

Transitions of C&C should be minimized for efficiency and risk control. Transfer of mission control from one control center to another may be done if appropriate system and operational expertise exists at both locations. Transfer of command from one control center to another may be done when the assets join or depart a larger segment of the mission. Appropriate C&C requirements and architectures will be established and maintained at each step in the program definition.

7.2.1.4.3 Operational Roles of the Crew and Ground Segment

Based on the above level of systems autonomy, the following provides a concept for the split of operational responsibilities between the exploration crew and the ground segment:

The exploration crew will:

- Exercise on-scene authority to make major changes to mission plans or content in situations where time does not permit ground segment consultation;
- Optimize ground-developed plans based on on-scene developments;
- Exercise C&C of dynamic phases (dockings, landings, departures, etc.);
- Perform preventive maintenance as required to keep spacecraft systems functioning within operational limits;
- Perform corrective maintenance;
- Provide functional redundancy to selected autonomous and ground-controlled operations; and
- Perform in-situ science investigations guided by a ground-based science program.

The ground segment will:

- Provide a central authority for authorizing major changes in mission plan or content—time permitting;
- Provide daily planning recommendations to the crew;
- Be capable of exercising C&C of all vehicles through all phases of flight. During dynamic phases of flight, control will be exercised through onboard automation and sequencing as appropriate;
- Provide operations and engineering expertise related to spacecraft systems operations;
- Perform systems trend monitoring and develop troubleshooting recommendations for systems faults that fall beyond the scope of onboard procedures or techniques;
- Provide software maintenance as required to keep spacecraft systems functioning within operational limits;
- Provide a strategic science plan responsive to exploration and discovery; and
- Provide crew psychological support to the extent allowed by communications technology.

7.2.1.4.4 Role of Automation

Communications time delays inherent in missions beyond Earth-Moon space must be accounted for when considering contingency cases and integrated responses to system malfunctions. **Figure 7-13** suggests a methodology for determining the appropriate application of onboard automation. The exploration architecture element design should be guided by the following principles:

- Onboard automation is appropriate for functions that cannot be practically managed by ground segment or crew intervention, or where automation significantly simplifies the effort required by the operator to manage the spacecraft systems;
- Automated functions should be applied across all elements in a consistent fashion, such that the operator does not have to account for which element or module they are in before they interpret their situation; and
- Onboard automation should be minimized or avoided entirely for functions where ground segment or crew intervention is adequate (e.g., non-time-critical functions on scales of hours or longer).

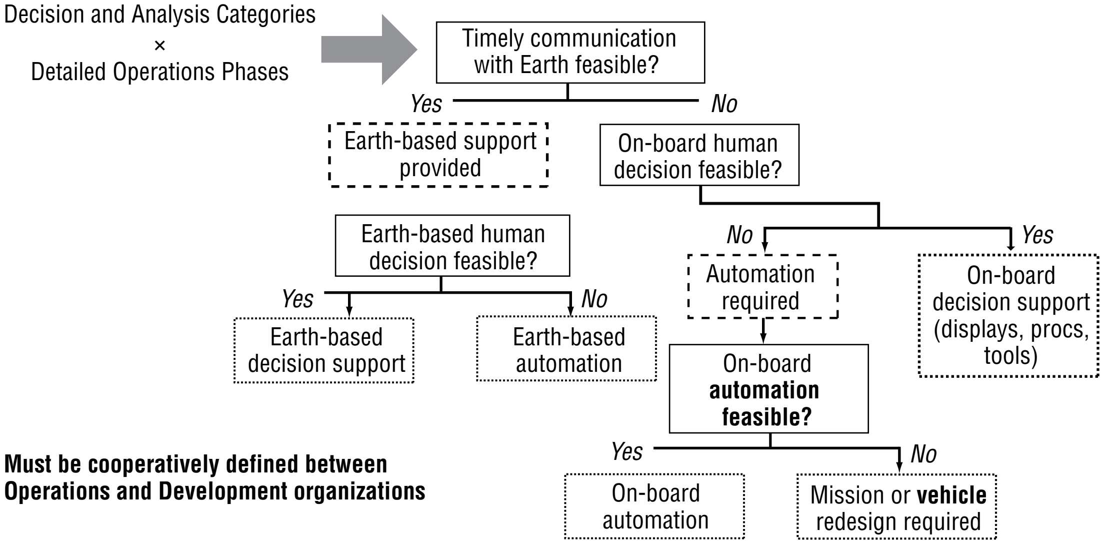


Figure 7-13. Role of Automation

7.2.1.5 Mission Support Segment Infrastructure

7.2.1.5.1 Dealing with Multiple Spacecraft

The ground infrastructure for operations, including facilities, simulators, and control centers, will have to simultaneously monitor, control, and simulate multiple spacecraft. Various combinations of Earth-orbiting spacecraft, lunar and Mars transit/orbiting/descending/ascending spacecraft, and surface habitats may be operating simultaneously. Separate control centers will be staffed and operated for each dedicated mission under a unified command and distributed control architecture. Simulators will be utilized to train crews on multiple spacecraft and be available for real-time failure support. Networks should be able to receive telemetry and communication from simultaneously operating spacecraft and transmit to the applicable control centers. Launch site facilities will provide storage capacity for multiple flight elements that are not in the mission processing flow. An overview of mission operations support infrastructure is provided in **Figure 7-14**.

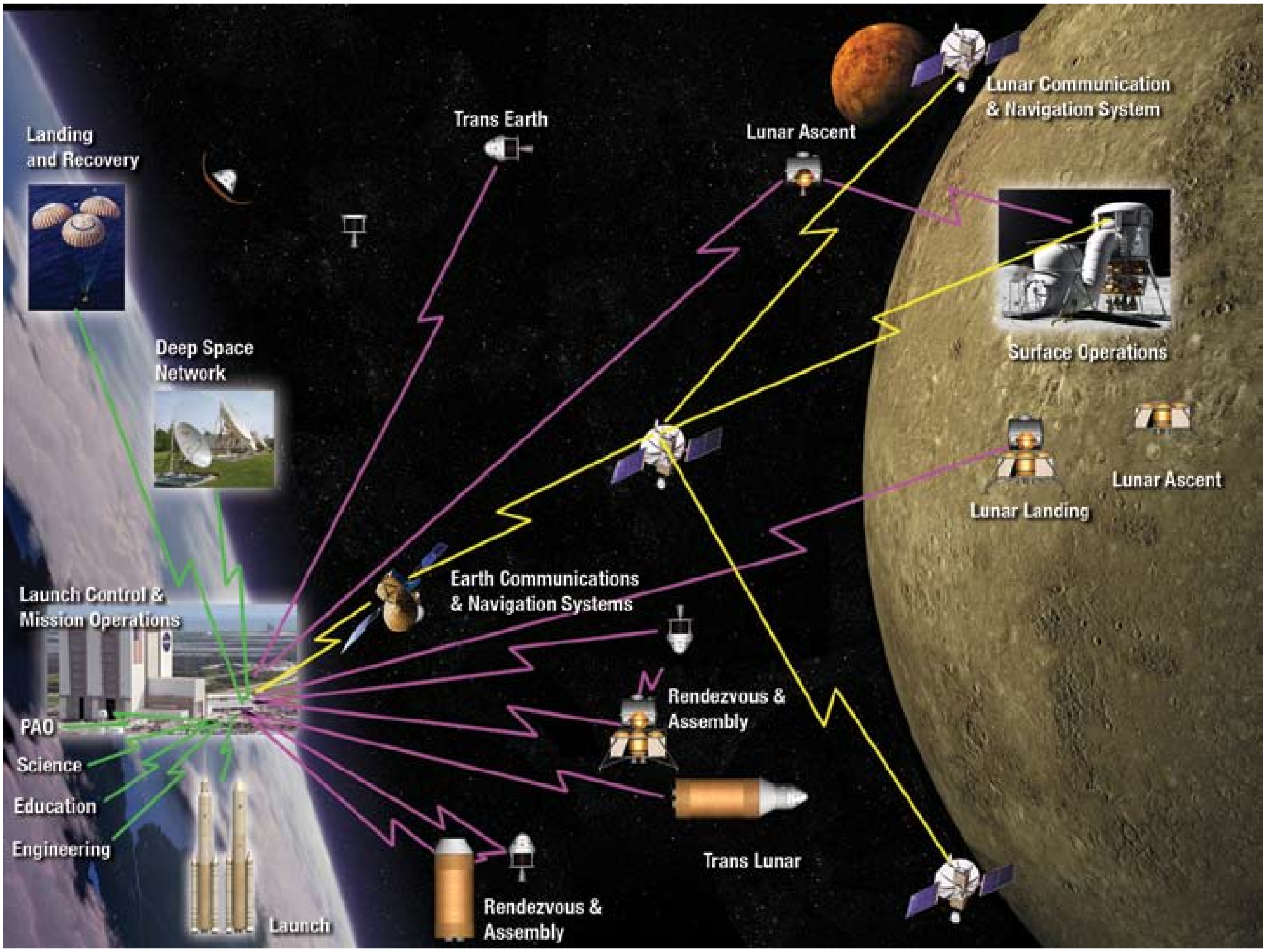


Figure 7-14. Mission Operations Communications Overview

7.2.1.5.2 Common Architecture and Integration

Multiple control centers and facilities will be operating for exploration missions with spacecraft operating in Earth orbit, lunar orbit, Mars orbit, and in transit to and from the surface of both celestial bodies. To reduce costs, all facilities should be designed with common architectures (processors, work stations, etc.) to the maximum extent practical. This will provide additional advantages, as facility redundancy will be increased and procurement simplified. The control centers should provide functions for both short- and long-term mission objectives. Ascent and descent to and from the surface will be highly dynamic phases but will occur in relatively short time frames. Surface operations and coast phases will be more quiescent and longer in duration. The control center architecture should have the capability to support both short- and long-term mission phases. While the same control center may be utilized for multiple mission types and phases, the ones operating simultaneously should be integrated in terms of communications.

7.2.1.5.3 Network Asset Management

During selected periods, or in response to failures, the communications network must be available to support operations 24 hours per day. The network should provide voice communications, spacecraft telemetry, command load, and operational message uplink/downlink capability to cover both scheduled and contingency communications. Contingencies include spacecraft systems failures requiring MCC notification or future assistance, solar flare alerts to the crew, etc. In addition, vehicles from multiple programs and missions will be operating simultaneously. This will require well-coordinated scheduling of communications and tracking network assets to avoid conflicts in nominal operations and prioritize allocation of assets during contingency operations.

7.2.1.5.4 Ground Data Management

A Ground Data Management System (GDMS) will be a collaborative environment that globally ties NASA, contractors, and suppliers together to the maximum extent practical while forming a key part of the systems data management concept. The GDMS concept comprises multiple databases that have the ability to exchange/access data in the most efficient manner possible, whether electronically or by other means. The GDMS should serve as the backbone for planning, process management, requirements management, problem reporting, configuration management, metrics capture, telemetry management, space flight element health management, ground systems health management, and data archival.

7.2.1.5.5 Communications and Tracking

A supporting communications and tracking infrastructure will be required to implement the C&C function. The evolution and deployment of this infrastructure must be integrated with the primary mission architecture. The communications systems should support a tiered hierarchy of operations, including:

- Local control (by flight crew) of deployed assets and EVA in proximity to the crewed elements;
- Local control with remote monitoring of deployed assets from within the crewed elements with ground support; and
- Remote monitoring and control of deployed assets via ground-based systems.

This hierarchy must support the following mission types and flight regimes:

- Near-Earth operations: launch support, early Earth-orbit operations, rendezvous, in space operations, lunar transit, and landing operations;
- Lunar Operations: orbit insertion, landing, surface operations, and Earth transit; and
- Mars Operations: Mars transit, Mars orbit insertion, surface operations, ascent, and Earth transit.

Given the 20-plus year span of this activity, the communications infrastructure should be evolutionary and seamless. Sizing and evolution of the infrastructure must envelope the total mission requirements in support of all active elements, including built-in redundancy for onboard and ground system anomalies, while supporting multiple and simultaneous lunar, Low Earth Orbit (LEO), and Martian operations. Adequate bandwidth for autonomous operations for all near-Earth and lunar activities must be provided. The autonomous activities can be conducted as demonstrations in support of initial robotic operations, including dockings, maneuvers, and transit operations. Intervehicle communication should be accessible by various vehicles and the ground crew to support onboard anomaly investigation and performance assessments of the various elements.

7.2.1.6 Human Spaceflight Transition and Competency Retention

Consistent with the above description of the primary phases of mission operations, a qualitative assessment of how existing mission operations facilities and core competencies would transition from their current Shuttle/ISS focus into supporting exploration needs was compiled. The following summarizes the strategies for each phase of operations, planning, training, and flying.

7.2.1.6.1 Mission Design and Activity Planning

The strategy for vehicle development support calls for DDT&E to be supported by experienced Shuttle/ISS controllers and mission support personnel with expertise in applying lessons learned and operations best practices for vehicle design.

While ascent and entry flight design for CEV is expected to be greatly simplified compared to the Shuttle, lunar trajectory analysis and design, precision surface landing, and abort core competencies must be redeveloped.

Core competencies in flight planning and crew time line scheduling should carry over directly to CEV lunar missions. Flight and ground software development competencies in systems and integrated procedures will be sustained by the ISS. C&C systems development and reconfiguration will be required as CEV flight experience accumulates.

7.2.1.6.2 Crew and Flight Controller Training

The strategy for training facilities is to retire Shuttle simulators and mock-ups after Shuttle standdown, develop CEV/exploration-unique simulators and mockups, continue sustaining ISS simulator and mockups to the end of the ISS program, develop new EVA trainer mockups for the Neutral Buoyancy Laboratory (NBL), and develop a surface analog facility for training surface operations.

7.2.1.6.3 Flight Execution

The strategy for flight execution is to have the flight control team makeup driven by mission and vehicle design while being founded on the essentials of human space flight. The operations team will be the smallest size that the technology, systems, and mission requirements will allow.

The MCC will require pre-Shuttle-retirement facility development to support early test flights (2009). Integrated planning system tools from the Shuttle can evolve to meet exploration needs, and significant amounts of Shuttle flight software can be reused for exploration missions.

7.2.1.7 Mission Operations Cost Estimate

Based on the above description, cost estimates were generated for conducting exploration flight operations through 2025 and are provided in **Section 12**, **Cost**, of this report. The following Ground Rules and Assumptions (GR&As) were used:

- Unique operations preparation and support to development are required for each new space vehicle or major upgrade of a space vehicle.
- LV performance margins will be maintained to avoid significant replanning of operational missions.
- Recurring ISS missions will use a single stable CEV, LV configuration, and mission design.

- Existing JSC MCC will be used with limited modification for all human missions and test flights of human-rated vehicles. Telemetry and command formats are assumed to be compatible with existing MCC capabilities.
- Recurring fixed costs for MCC use will be shared by the exploration architecture after the Shuttle stops flying in proportion to facility utilization.
- New development is required for training simulators, as potential for reuse of existing simulators is very limited.
- Simple mission planning and operations are assumed for test flights and CEV flights to the ISS.
- Complex and highly integrated mission plans are required for initial lunar sorties.
- Simple and quiescent surface operations are assumed for extended lunar stays.
- Crew and ground tasks are considerably simpler than those of the Shuttle during critical mission phases.

The fundamental findings of this costing activity were:

- Mission operations cost is largely dependent on the number of unique space vehicles and annual crewed flight rate.
- Mission operations cost is generally independent of the number of launches involved in a single crewed mission.
- Mission operations cost is generally independent of the launch architecture.

7.2.1.8 Communications Architecture Study Assumptions

As part of this study, the ESAS team established a set of assumptions related to operational support infrastructure needed to conduct CEV flights to and from the ISS and the lunar campaigns through 2025. These assumptions were based largely on the work of NASA's Space Communications Architecture Working Group (SCAWG).

LEO needs were assumed to be satisfied by the existing Space Network Tracking and Data Relay Satellite System (TDRSS) constellation through 2025, assuming the planned TDRSS upgrade deployment occurs in the 2015 time frame.

Similar to Apollo, initial lunar sortie missions will be supported by Earth ground stations. This assumption is based on no identified requirement for communications coverage for critical maneuvers performed on the lunar backside. The SCAWG recommendations call for a Ka-band-array on the ground for providing high-bandwidth support. If exploration objectives are limited to polar and near-side sorties, the ground-based Ka-array capability should be sufficient when augmented with a few S-band ground antennae. This concept is already in development as an upgrade program for the Deep Space Network (DSN) scheduled to begin in 2008. The ESAS assumptions would augment this capability through additional ground site investments in capacity and control systems to make the system available for use on lunar missions by 2018. **Figure 7-15** depicts one possible architecture for supporting lunar sortie missions.

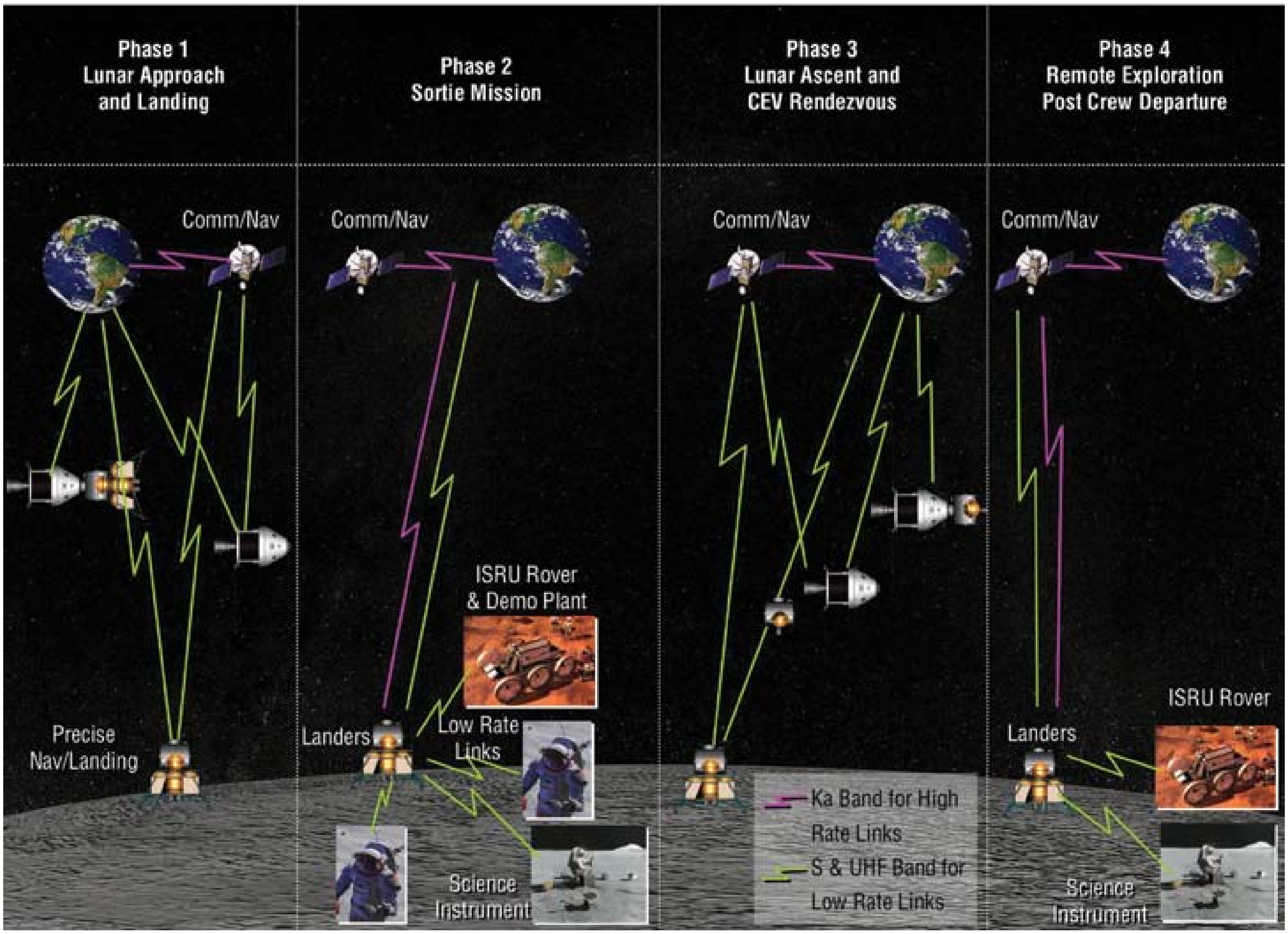


Figure 7-15. Lunar Sortie Surface Communications

A requirement for communications and navigation that supports lunar far-side operations will exist to enable global lunar access for surface operations. To meet this requirement, a lunar relay satellite constellation will be needed. SCAWG assessments have converged on the recommendation to place a constellation of three relay spacecraft with the orbital apoapsis beneath the south pole, thus increasing the viewing, or dwell time, above that region. For example, phasing the spacecraft can ensure that two of three satellites are within view of the south pole. Deployment of such a system should be closely coupled with the design of a lunar campaign (initial global sorties versus outpost buildup at single site, etc.). **Figures 7-16** and **7-17** depict one possible architecture for supporting lunar outpost missions.

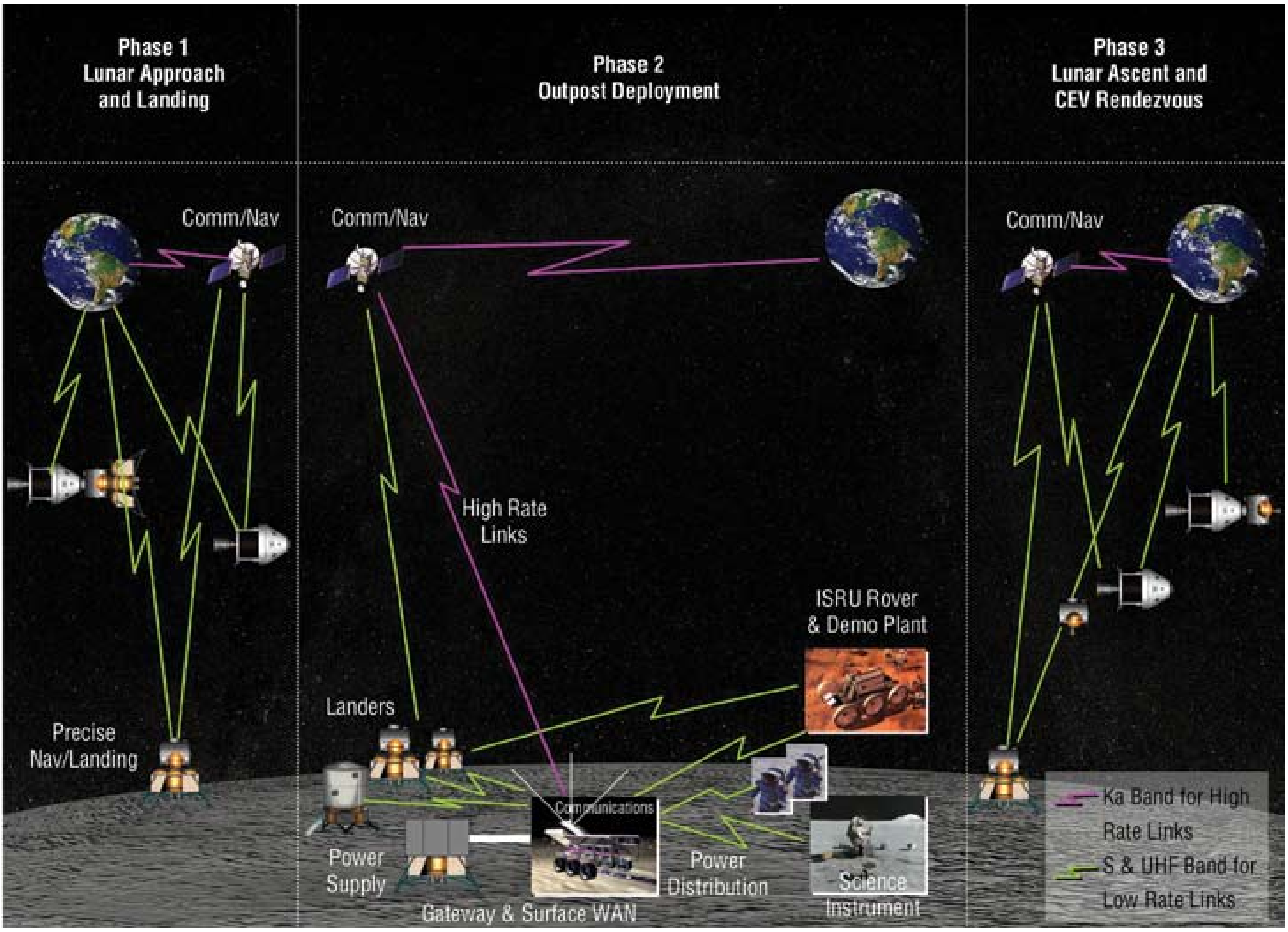


Figure 7-16. Lunar Outpost Surface Communications

During the course of this study, the initial costing of lunar relay spacecraft was based on a TDRSS derivative. The SCAWG also defined a “small sat” concept that is scaleable according to operational needs and would involve gradual capability buildup at a much lower cost. The ESAS team recommends that the SCAWG investigate alternatives to procurement of dedicated LVs for deployment, perhaps integrating them instead onto EDSs of early lunar sortie missions.

Augmentation of the early lunar robotic programs should be aggressively pursued. The Lunar Reconnaissance Orbiter (LRO) and subsequent orbiters should carry independent communications and navigation relay packages designed with at least a 5- to 10-year lifetime. This augmentation builds on capabilities successfully demonstrated on Mars requirements for lunar robotic precursor orbiters. Robotic (and crewed) lunar landers should be augmented to assure communication and navigation relay after primary science/engineering objectives are completed.

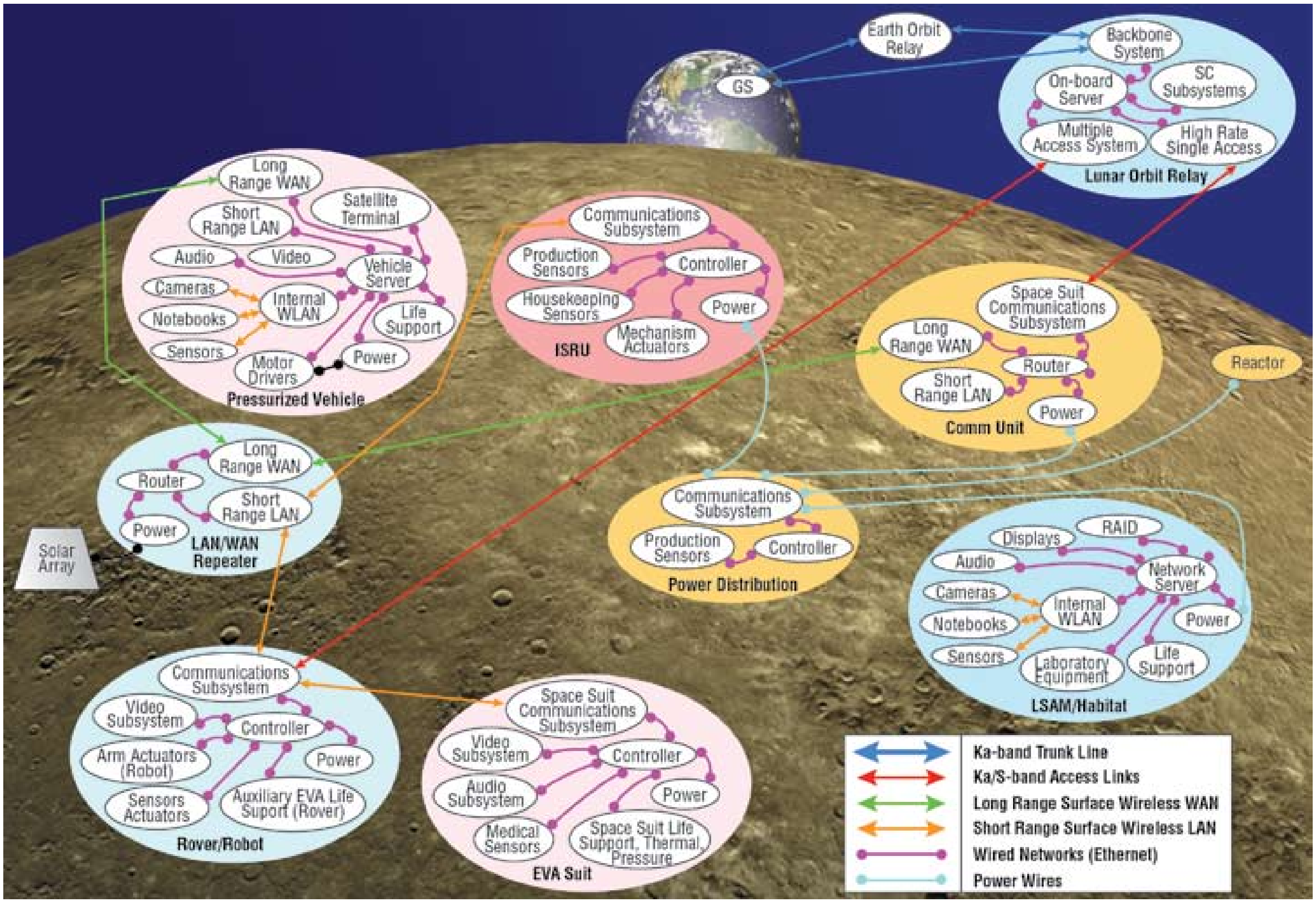


Figure 7-17. Communication and Navigation Networks

7.2.2 Operational Considerations for Effective Exploration Architectures

"Space systems engineering is the art and science of developing an operable system capable of meeting mission requirements within imposed constraints, including (but not restricted to) mass, cost, and schedule."

– M. Griffin,

Space Vehicle Design

2nd Edition

The feedback loop and linkages between operational performance and system design for future exploration missions are particularly important if NASA is to maximize learning during the long-term development process that will be required. Achieving the ambitious space exploration goals will require optimal learning from each mission and the ability to apply lessons learned to future missions and system development cycles. The Agency will need to create an organizational control structure for Safety and Mission Assurance (S&MA) that is self-reflective, self-analytical, sustainable, and capable of compiling and applying lessons learned.

With this goal in mind, the ESAS team addressed the following topics related to the overall approach to effective exploration architecture definition:

- Flight Safety and Mission Reliability,
- Design for Human Operability,
- Commonality,
- Maintainability,
- Interoperability,
- Habitability,
- Supportability,
- Environmental Considerations,
- EVA,
- Communications and Tracking, and
- Software.

7.2.2.1 Flight Safety and Mission Reliability

7.2.2.1.1 Design Simplicity

Design simplicity is a prime criterion for design trade-offs and involves minimization of moving parts and interdependence on other systems, ease of operation, and maintenance by the crew. Simple systems require less operations attention and fewer operator constraints, necessitate less training, and enhance reliability for long-duration missions. However, to paraphrase Albert Einstein, “everything should be made as simple as possible, but not simpler.” For example, there will be functions that necessitate adding complexity during the design phase in order to achieve the needed performance and reliability.

7.2.2.1.2 Design Robustness

All architecture elements should allow for safe execution and operation toward completion of all primary mission objectives in the presence of any single credible systems failure. Crew safety shall be assured for any two independent credible failures sustained at any point in the mission. Robustness can be achieved through redundancy, generous design margin, or demonstrated high reliability.

7.2.2.1.3 Redundancy

High-reliability systems are preferred over multiple levels of redundancy where possible to reduce system complexity. Where redundancy is implemented, dissimilar and full-capability systems are preferred. Minimum requirement and performance backup systems are less preferable than full-capability systems. Redundant paths such as fluid lines, electrical wiring, connectors, and explosive trains should be located to ensure that an event that damages one path is least likely to damage another. All systems incorporating an automated switch-over capability must be designed to provide operator notification of the component malfunction, confirm that proper switch-over has occurred, and confirm that the desired system is online.

7.2.2.2 Design for Human Operability

All sensing components associated with enabling the crew to recognize, isolate, and correct critical system malfunctions for a given vehicle should be located onboard that vehicle and be functionally independent of ground support and external interfaces. Two independent instrumented cues are required for any major change in the nominal mission plan. The source of these cues can be space vehicle displays, alerts, and downlink telemetry. Cues are not independent if space vehicle and ground indications are from the same sensor. Redundant sensors are required if two independent cues of a failure cannot be obtained. No requirement should exist for more than two active sensors for a particular parameter on an individual system.

The crew should have the ability to intervene and override any onboard decision regardless of sensor indications. A central objective of the sensor systems is to facilitate the situational awareness of both the crew and remote operators on Earth or another vehicle. The design should allow the operator to make a rapid assessment of the current situation, including the exposure and investigation of off-nominal states.

The crewed vehicle design should allow for the crew to provide functional redundancy to the automated and Earth-in-the-loop systems where practical. Examples of this functionality include orbit determination, maneuver design and execution, and rendezvous and docking operations without the aid of ground control. Crewed vehicles should require crew consent for irreversible actions where practical with respect to human reaction and decision times. Examples of this include a commitment to injection, deorbit, and trajectory correction maneuvers. In the event the need for uncrewed operation arises due to crew incapacitation or maximizing effective use of crew time, the ground crew should be able to control all crewed vehicle-critical functionality.

Crewed vehicles will provide the flight crew with insight, intervention capability, control over vehicle automation, authority to enable irreversible actions, and critical autonomy from the ground. Display and control interfaces will be simple and intuitive. Presentation of onboard systems' status information to the crew should be done in a consistent manner across all flight elements and should be based on common, well-documented practices of measure, iconography, and graphical standards. System design must preclude any failure mode requiring unreasonably swift human action to prevent a catastrophe.

7.2.2.3 Commonality

Commonality at the component and subsystem level should be applied to and across all elements of the exploration system. Strict adherence to commonality will minimize training requirements, optimize maintainability (particularly on long-duration missions), and increase operational flexibility. Design for commonality and standardization of hardware and hardware interfaces will simplify provisioning of spares, minimize the number of unique tools and amount of unique test equipment, and enable substitution between elements. This applies to hardware at all levels and among all architecture elements, including power and data buses, avionics circuit card assemblies, electronic components, and other assemblies such as pumps, power supplies, fans, fasteners, and connectors.

Commonality applies to hardware components and similar software functions across the elements. Vehicle subsystems should be designed so that consumable items can be interchanged with other common subsystems on the overall vehicle and other vehicles. Unattended systems should not have catastrophic failure modes requiring immediate human intervention.

7.2.2.4 Design for Human Operability

7.2.2.4.1 Maintainability

Systems and hardware must be designed to simplify maintenance operations and optimize the effective use of maintenance resources. The mass and volume of spares and other materials required for maintenance and the overall effect on system availability must also be considered. Standard design approaches to simplifying maintenance operations should be employed. These approaches include reduction of the need for EVA maintenance to the greatest degree possible, ensuring easy access to all items that may require maintenance, unambiguous marking of lines and connectors, and implementation of the minimum number of standard interfaces for transfer of power, liquids, gases, and data. System design should ensure that pre-maintenance hazard isolation is restricted to the item being maintained. Maintenance impacts to other operations should be minimized. Due to the time and distance effects on the logistics of re-supply and the effects of hardware failure on long-duration mission risk, hardware should be designed from the initial design phase for ease of repair and maintenance. This involves a shift from the historic LRU philosophy of spacecraft to a philosophy of having the capability for disassembly and repair of the failed unit.

7.2.2.4.2 Interoperability

Systems (or components of systems) should be interoperable with similar systems or components in other architecture elements where possible. Common standards should be established for power systems, operating environment envelopes, consumable or replaceable components, displays and controls, software, communication capabilities and protocols, and other systems attributes. This approach will minimize training requirements, enhance the usability of portable or transferable equipment, and reduce logistics requirements.

7.2.2.4.3 Supportability

The logistics footprint required to support exploration missions must be minimized. Strategies to achieve this objective include broad implementation of commonality and standardization at all hardware levels and across all elements, repair of failed hardware at the lowest possible hardware level (as determined on a case-by-case basis by detailed analyses), and manufacture of structural and mechanical replacement components as needed. Prepositioning of logistics resources (spares and consumables) should be used to distribute logistics mass across the architecture elements and reduce mission risk by staging critical assets at the destination prior to committing human crew. Utilization of in-situ surface resources for production of propellants, breathing gases, and possibly consumable water could significantly reduce the mass that must be delivered to planetary surfaces.

A comprehensive inventory management system that monitors and records the locations and quantity of logistics items should be implemented. The system should accommodate crew interaction while also performing routine audits and item tracking without active crew involvement.

7.2.2.5 Environmental Considerations

The vehicle design should minimize environmentally induced constraints on ground and flight operations while also minimizing sensitivity to extreme variations in both natural and induced environmental conditions. Hardware should be able to survive long periods with no power and be able to return to operation from such a frozen state. Space weather information and alerts should be received directly from the weather sentinels by operational vehicles without having to be processed by Earth stations. Space weather alerts should be transmitted automatically. Crewed vehicles should be equipped with space weather sensors for radiation event alerts where practical. Space radiation should only be accounted for in the design to a risk level commensurate with other sources of risk to crew safety.

7.2.2.6 Habitability

Habitability must be a prime consideration in the design of all crew vehicles and habitats. Convenient engineering design solutions (functional adjacencies) must not compromise habitability. Habitable volumes will provide a pressurized, temperature- and humidity-controlled atmosphere for the crew for all nominal phases of flight except Earth launch and landing. Habitable volumes will also provide protection for the crew against failures that would compromise the habitable environment. During long-duration missions, habitable volumes must allow for simultaneous activities such as sleeping, eating, performing hygiene functions, and exercising, and for off-duty activities with separate and dedicated volumes. Privacy for sleeping, hygiene, and off-duty times is essential.

7.2.2.7 Extra-Vehicular Activity (EVA)

7.2.2.7.1 Habitat Assembly

As the primary focus of planetary operations should be toward exploring the planetary surface(s), EVAs should be minimized in design. Although a crew transportable rover is not envisioned for these EVAs since these tasks will be located within a short distance from the habitat, a small rover to assist with tool transportation may be desirable.

7.2.2.7.2 Habitat Maintenance

The majority of maintainable items should be located internal to the habitat in order to expedite maintenance activities.

7.2.2.7.3 Surface Exploration

The surface mobility systems for a lunar outpost should be sized to support up to five EVAs per week. These EVAs, while initially local to the habitat, will eventually require rovers (pressurized for excursions greater than approximately 10 km) with EVA resupply capability and possible EVA way stations to support EVA resupply in case of a walk-back scenario. This will also require a lightweight and highly mobile suit that can withstand the dust contamination concerns and will be of sufficient crew comfort to support this EVA frequency. This phase of operation may drive the need for a suit separate from the launch and entry/contingency EVA suit in order to withstand the dust, abrasion, radiation, and thermal environments and offer pressurized suit comfort and a self-contained life support system.

7.2.2.7.4 Logistics or In-Situ Resource Utilization (ISRU) Retrieval

EVAs may be required to retrieve the resupply capabilities from logistics modules if those modules are launched and landed separately from the habitat. ISRU may require EVA to transport the manufactured resources back to the end-item location.

7.2.2.7.5 Distance from Habitat

If the tasks are located farther than the emergency return walking distance (approximately 30 minutes), way stations to provide suit consumable resupply should be provided. This would not only enable refill of the suits in an emergency situation to complete the walk back to the habitat airlock, but could also extend the EVA for those tasks without spending an inordinate amount of time continuing translation back to the airlock for resupply. These way stations would not necessarily need to be a permanent infrastructure, but could be laid down on the way out and picked up on the way back during the sortie (which would somewhat constrain the return path). If a particular translation route is frequently used, it may be cost-effective with regards to EVA time to leave these stations in place.

Another method to provide this resupply capability would be to allocate a consumable resupply on the rover, although the distance would still be constrained to a full suit resupply for walk-back with no way stations available (either on the crew transport rover or smaller tool-carrying rovers). A string of way stations might be required if the traverse distance from the airlock exceeds 1 hour. If a rover is used, a string of way stations might be required to maintain a walk-back capability. If no way stations are implemented, the rover distance from the habitat may be constrained by the distance a crew member can walk without resupply.

7.2.2.7.6 Airlocks and Dust Mitigation

Dust will be one of the most problematic issues for both lunar and Martian EVAs. Although the perception of the nuisance factor of dust varied between Apollo crews, all crews except Apollo 11 experienced some issues with lunar dust. The longer a crew was on the lunar surface (including multiple EVAs per mission) and the more intricate a particular mission's EVAs were, the more dust-related problems were experienced. Apollo J-missions, which spent 3–4 days on the lunar surface and conducted three EVAs on each mission, experienced the most problems with lunar dust. Dust got into any unclosed or unsealed volume through almost any size hole, including suit pockets, sample storage bags, nooks and crannies on the Lunar Roving Vehicle (LRV), internal mechanisms of cameras, and onto thermal blankets of surface experiments and communications systems.

The effects of lunar dust were specifically:

- Fouling of mechanical systems such as tools, suit parts, and rovers;
- Degrading thermal control by changing the reflectivity of external coverings;
- Degrading optical surfaces;
- Abrasion of glove coverings and other equipment;
- Irritation of the skin, particularly the hands and glove wear points (e.g., knuckles and fingernails); and
- Irritation of the mucous membranes and eyes.

Despite increased cleaning efforts as part of later J-missions, no cleaning methods were completely effective at removing dust from suit parts prior to entering the Lunar Module (LM). Each lunar mission from Apollo 12 onward experienced problems associated with tracking dust into the LM. While brushing down suits, kicking off boots on the LM ladder, and jumping up and down on the LM footpad prior to ascending the LM ladder were all somewhat effective, no mission was able to completely prevent the introduction of dust into the LM cabin, regardless of how enthusiastically the cleaning methods were applied.

Although the pressure garment was effective at keeping dust out of the interior of the suit, later missions introduced dust into the suit on the second and third EVAs after crew members doffed suits and picked up dust on hand and foot coverings. Also, Velcro to assist in crew restraint during zero-g operations covered the LM floor. Velcro proved particularly effective at collecting lunar dust, which was picked up by the crew and introduced into the suit through handling and donning. The Apollo 17 crew's general consensus was that their suits would not have been able to perform a fourth EVA.

Although the LM Environmental Control and Life Support System (ECLSS) was able to clean the airborne dust from the LM atmosphere on the lunar surface during crew sleep periods and remove floating dust from the atmosphere after LM ascent stage orbit insertion, there was still noticeable dust in the LM atmosphere when the Command/Service Module (CSM) and LM docked. Apollo 17 crew in particular noticed on-orbit eye, nose, and throat irritation when helmets and gloves were doffed prior to transfer of cargo from the LM to the CSM. This not only impacts the suit functionality (bearings, visors, etc.), but also potentially internal operations if not sufficiently handled. Several potential available options include utilizing a suit-washing station prior to bringing the suits into the habitable volume or utilizing an airlock arrangement so that suits are seldom brought inside (e.g., a suit port concept). A combination of both of these may be required, as the suits should eventually be brought inside for maintenance or return to the lander vehicle.

7.2.2.7.7 Surface Habitat Pressure and Atmosphere

In order to increase the margin of crew safety and the work efficiency index (so that the frequency of exploration EVAs can be performed), it is imperative to have a low habitat pressure combined with an increase in oxygen partial pressure. Reducing cabin pressure and increasing oxygen partial pressure can allow for conservative pre-breathe protocols, thus reducing crew day-length concerns and offering a high degree of protection against Decompression Sickness (DCS). Although some amount of final in-suit pre-breathe will be required for all credible suit pressures, pre-breathing can be minimized with the proper cabin atmosphere selection. Pre-breathe protocols should be simple and should not require dedicated exercise equipment and complicated infrastructure with multiple single-point failures. In addition to the resulting habitable design impacts, all long-term crew health countermeasures should take this reduced pressure and increased partial pressure environment into consideration.

7.2.2.7.8 EVA Transfer to Ascent Vehicle

The EVA to transfer the crew back to the planetary ascent vehicle from the habitat is a scheduled EVA for safe crew return and is, therefore, of the highest criticality. As such, this phase may drive the amount of EVA suit redundancy.

7.2.2.8 Communications and Tracking

The following summarizes the recommended attributes of an effective communications support infrastructure for exploration missions:

- Be capable of sustaining uninterrupted, multi-year activity involving multiple vehicles;
- Provide operational capability to support simultaneous near-Earth and lunar or near-Earth and Martian operations;
- Limit the number of unique communication subsystems on the various operational elements through commonality in communication components and data standards;
- Allow for modular upgrades over the life of the program;
- Provide flexibility for contingency ground operations so that no site, tracking station, or facility is a single point of failure; and
- Ensure that C&C interactions between launch processing facilities, MCC, and key element integration sites are consistent and have the appropriate diversity in routing and reliability for the missions operations.

7.2.2.8.1 Vehicle Telemetry and Command

The infrastructure should provide near-continuous telemetry and command with all elements. Communications systems on all vehicles will continuously transmit engineering and health information and are always receptive to commands, either directly to and from Earth or through relay assets. Omnidirectional antennae should provide emergency link capability to avoid dependence on accurate pointing and attitude control in off-nominal conditions where practical.

All vehicles should provide redundant command reception capability, including the ability to remotely restart the element’s primary computers. Vehicle safe modes will automatically transmit a 911 signal to help ascertain vehicle status and location. This will be a minimal keep-alive communications capability to help locate assets from Earth, lunar, or Martian operations.

7.2.2.8.2 Voice Communications

The integrated architecture should provide at least two primary channels of operational full-duplex voice communications per crewed mission activity. At least one additional independent backup voice channel should also be provided. The capability for voice communication between the crew and ground segment should be provided when appropriate.

7.2.2.8.3 Video Communications

The integrated architecture should provide at least one channel of commercial quality video to the ground segment. At least one channel of bidirectional video should be provided for operational use and at least one additional channel of bidirectional video should be provided for crew psychological support.

7.2.2.8.4 Intervehicle Communication

The concept that the monitoring and control of a vehicle from another vehicle should be as identical as possible to the monitoring and control of that vehicle from Earth is a guiding operational concept for communications. This level of monitoring and control between vehicles should be available whenever the two vehicles are involved in coordinated operations such as rendezvous, formation transit, and surface exploration. Communications links between such vehicles that provide the availability and bandwidth needed to support the operations activities are required. Relay communications satellites or stations should be provided in the architecture where line-of-sight is not available between such vehicles.

7.2.2.8.5 Communications Security

Near-Earth command links for robotic, manned, and autonomous operations should be protected and secure. Earth access systems and facilities must also be secured.

7.2.2.8.6 Space Weather Monitoring

The infrastructure should ensure that space weather information and alerts can be received by operational vehicles directly from the weather sentinels without having to be processed by Earth stations. Space weather alerts should be transmitted automatically. Crewed vehicles should be equipped with space weather sensors for radiation event alerts.

7.2.2.8.7 Ground Testing Support

Pre-flight test and integration of the vehicles and ground systems should use the same communications systems and mission control facilities used in flight. Earth test beds used for diagnosis and response testing while the corresponding vehicles are in flight should also be monitored and controlled using flight-like communications and should be directly operable by the mission control facility.

7.2.2.8.8 Radio Frequency (RF) Spectrum Assignment

A key goal is to ensure compatibility among all U.S. and/or international elements. RF and optical spectrum frequencies that provide for growth and isolation from interference must be assigned.

7.2.2.8.9 Navigation Support

The navigation architecture should address two distinct operational regimes:

- In-space navigation and guidance support for critical in-space maneuvers between the Earth's surface and the exploration destination; and
- Surface navigation assets to support human and robotic operation on destination surfaces, including navigation aids for precision landing and the tracking of asset position on the surface.

Both radiometric tracking using external resources (such as Earth) and RF or optical tracking using only intravehicle resources can independently provide the required accuracy to achieve the mission objectives. Navigation support for critical in-space maneuvers should be highly robust and reliable. Ground-based systems are preferred over space-based systems in terms of robustness, thus providing a greater number of assets with the greatest flexibility and robustness in tracking network diversity.

7.2.2.9 Software

In a recent study of the role of software in space flight mishaps, many cultural and managerial flaws manifested themselves in the form of technical deficiencies, including:

- Inadequate system and software engineering,
- Inadequate review activities,
- Ineffective system safety engineering,
- Inadequate human factors engineering, and
- Flaws in the test and simulation environments.

Software standards are required to avoid the cost of supporting dissimilar systems and architectures. Similar software functions across all architectural elements, such as Fault Detection, Isolation, and Recovery/Reconfiguration (FDIR/R) or other vehicle management applications, should be developed to a common set of standards.

Computer advancements, the emergence of highly reliable decision-making algorithms, and the emphasis on efficiency make an increased use of automated systems possible. However, full automation is often not practical for some human space flight applications. The program must weigh the DDT&E cost of placing functions on board (including factors such as design flexibility, verification/validation of flight software, and sustaining engineering during flight operations) against the cost of performing functions on the ground for functions where reaction time is compatible with light-time communications delays.

Software design and architecture should support the capability for rapid changes according to changing program and operational needs. This capability should support major version-level updates as well as both prelaunch and in-flight, time-critical, small-scale fixes and parameters. The design cycle in ISS was so extensive that in-flight changes or operational workarounds were almost always required by the time the operations community had access to the final software versions. The software should be modular and provide a capability to turn a function on and off as needed. The design must ensure minimum total system impact from programming changes and additions.

Additionally, software design should offer flexibility to allow the incorporation of upgraded and/or new LRUs with minimal impact, such as use of industry standard interfaces and preserving performance margin. For example, Shuttle upgrade studies with a Global Positioning System (GPS) and Space Integrated GPS Instrumentation (SIGI) have demonstrated the difficulties of integrating recent technologies with older flight software. Rather, a balance must be found between how much human operators trust automation and how much benefit and cost-savings automation provides. This balance may result in an intermediate level of automation somewhere between full-computer responsibility and full-human responsibility. For example, the Space Shuttle Program has found that the appropriate balance of computer and human authority gives launch abort authority to human launch controllers when there is enough time to make a decision. Similarly, computers are given launch abort authority for some time-critical failures.

Distributed control systems should change software states based not only on events (e.g., commands completing), but also on telemetry from lower-tiered units. For multi-tiered systems, command validation at each tier should only include parameters controlled by that tier. Commands should be passed to lower tiers to verify other parameters under their control, with the response then passed back accordingly. Message integrity is the only validation that should be performed at all levels.

Onboard crew should have a method to view any cyclic data parameter. Any parameter that might need to be changed should not be hard-coded. This includes timeout values, Caution and Warning (C&W) limits, etc. These parameters should be changeable by command as well as by some method to set defaults and make large changes at one time. The process for creating and releasing reconfiguration data should accommodate quick-turnaround changes. Testing requirements should be defined in advance to identify cases where the products do not need to be tested on a simulation of the vehicle and, therefore, can be developed more quickly. All hardware interface controls should have a software override/equivalent in case of failure.