Hercules Single-Stage Reusable Vehicle (HSRV) Operating Base

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NASA Kennedy Space Center
Major: Aerospace Engineering
NIFS Fall Session
Date: 17 Nov 2017

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Conceptual design for the layout of lunar-planetary surface support systems remains an important area needing further master planning. This paper explores a structured approach to organize the layout of a Mars-based site equipped for routinely flying a human-scale reusable taxi system. The proposed Hercules Transportation System requires a surface support capability to sustain its routine, affordable, and dependable operation. The approach organizes a conceptual Hercules operating base through functional station sets. The station set approach will allow follow-on work to trade design approaches and consider technologies for more efficient flow of material, energy, and information at future Mars bases and settlements. The station set requirements at a Mars site point to specific capabilities needed. By drawing from specific Hercules design characteristics, the technology requirements for surface-based systems will come into greater focus. This paper begins a comprehensive process for documenting functional needs, architectural design methods, and analysis techniques necessary for follow-on concept studies.

Nomenclature

ADS	=	Ascent/Descent System
ATLS	=	Abort/Terminal Landing System
DSG	=	Deep Space Gateway
EDL	=	Entry, Descent, and Landing
EZ	=	Exploration Zone
HCRV	=	Hercules Crew Rescue Vehicle
HPDV	=	Hercules Payload Delivery Vehicle
HPSF	=	Hercules Propellant Storage Facility
HSRV	=	Hercules Single-Stage Reusable Vehicle
ICE	=	Internal Combustion Engine
IPPF	=	In situ Propellant Production Facility
LMO	=	Low Mars Orbit
MEL	=	Master Equipment List
MPCF	=	Mobile Propellant Conditioning Facility
RCS	=	Reaction Control System
TPS	=	Thermal Protection System

I. Introduction

There is a growing recognition of the need for sustainable transportation to and from lunar-planetary surfaces. There are also a number of reusable lander systems proposed to operate on Mars for the purpose of growing bases

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and settlements.[1,2,3] Supporting architectures on the surface for reusable flight systems require greater engineering attention. For example, fundamental and practical siting criteria of departure and arrival stations are lacking. Sizing of equipment needed for refueling, maintenance, and resupply also require more examination.

With the above master planning criteria in mind, this paper examines an organizational construct for an operating base using the Hercules Single-Stage Reusable Vehicle as an example. This operating base is an important part of a larger exploration zone including sustained human habitation. These exploration zones, if sustainable, can grow to become human settlements.

II. Reusable Hercules System Background

The HSRV concept is a multi-functional, single-stage, reusable vehicle designed to operate between Low Mars Orbit (LMO) and the Mars surface base utilizing in situ produced propellants, specifically oxygen and methane. Its primary function is cargo and crew transport between LMO and the Mars surface base. For Mars, the initial HSRV landings would be uncrewed and single-use for flight, focusing specifically on emplacement of the necessary surface infrastructure of a Mars base. This includes power, thermal, habitation, mobility, in-situ resource acquisition and processing, and propellant production/storage infrastructure. The HSRV operates initially as a one-way lander, repurposed for use as part of the base infrastructure after its flight. Once a functioning base that is generating propellant is established, the campaign will transition into a build-up phase where reusable HSRV systems become operational so that the base can grow affordably.[4]

A. Hercules Traffic Model Background

The Hercules concept proposes an orbital node at Mars located in a 500 km circular LMO at an inclination that offers access to the selected base site. This node, delivered by the Hercules Payload Delivery Vehicle (HPDV), would allow payload to be transferred between future HPDV vehicles and the HSRV. In addition, it would serve as a crew transfer port, for both arriving and departing crews. The HSRV is expected to operate between the surface base and the LMO node twice per Earth year, and the HPDV arrives at the node less frequently, perhaps only once per synodic cycle (2.2 Earth years). Once the HSRV is fully operating in reusable mode, fewer interplanetary missions delivering new HSRV's are needed, thus reducing the performance burden on the interplanetary transportation systems.[5]

B. Hercules Transportation Flight Systems (HSRV)

1. Overall Description

The HSRV concept is a single-stage, reusable vehicle that operates from the Mars surface base utilizing oxygen and methane propellants manufactured in situ. Its primary function is cargo and crew transport between LMO and the Mars surface base.

The vehicle has four sections:

1) Nose Section
2) Crew Module
3) Payload Section
4) Ascent/Descent Section

Each of these sections are separable and serve multiple functions in the architecture. For early demonstration and base infrastructure buildup flight, the HSRV operates in flight once, and is then repurposed to operate as part of the base infrastructure. For example, the ascent/descent section serves as a propellant storage facility once landed on the surface.[6]

Nose Section

The nose section design for both the cargo or crew variants includes structures and mechanisms; an external Thermal Protection System (TPS); the Abort/Terminal Landing System (ATLS) tanks, feed and engines; the Reaction Control System (RCS); a power generation and tank pressurization system; and the vehicle avionics systems.

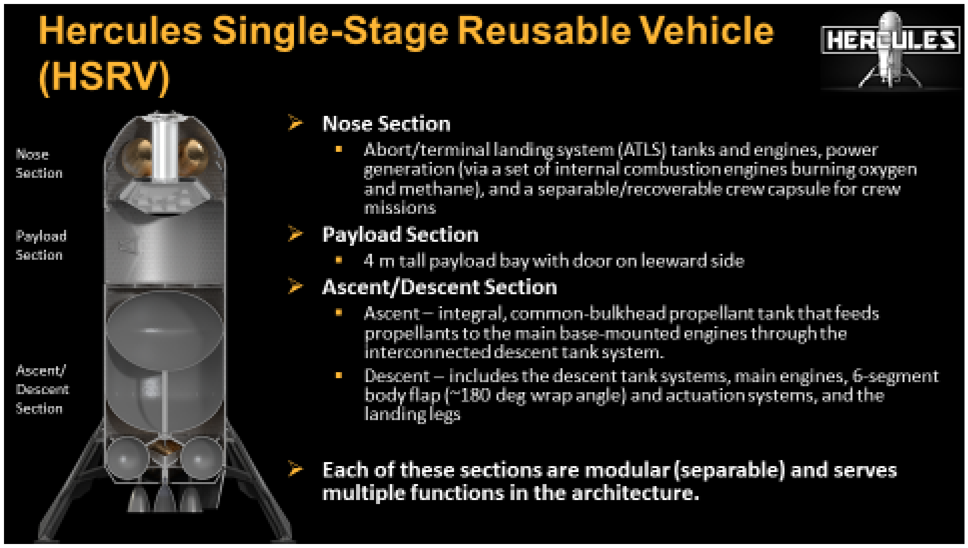

Figure 1—Conceptual vehicle layout

The nose layout is a 60-degree sphere-cone that transitions to a cylindrical shell. A retractable door, located at the tip of the spherical section, exposes a standardized mechanical docking system for docking to the Deep Space Gateway (DSG), the LMO node, or to other vehicles. The base of the nose section includes a conical structural adapter that supports the ATLS tanks.

The nose section includes two power generation and tank pressurization systems that support the entire vehicle during ascent, on-orbit, and Entry, Descent, and Landing (EDL). Each system uses an internal combustion engine (ICE) burning gaseous oxygen and gaseous methane drawn from the ATLS tanks, each producing up to 40 kW of peak power (at 100% ICE throttle) for short duration peak electrical loads. At idle, each ICE continuously provides 3 kW of electric power for the vehicle, consuming ullage and boil off gases at low rates. The ICE is also used to generate pressurization gases for the ATLS and ADS tanks, on demand, from the liquid propellants using the ICE cooling loop to heat and vaporize the liquid propellants.[7] An item for consideration would be the potential use of the ICE for power during lunar night. Whether the ICE would be onboard the Hercules elements, or on separate surface equipment, can also be traded.

A means of accessing the nose section from the surface needs to be examined. A number of options may be appealing depending upon the time of implementation. The location of maintenance and repair also needs to be explored. For example, is the preferred location to repair equipment in the nose section better based on orbit, or on the surface based on accessibility?

Crew Module

For the crewed configuration only, a crew capsule, suspended from below, mates to this adapter connecting it to a pressurized tunnel, linking it to the docking port, which enables the crew to egress/ingress the capsule and the HSRV in zero-g. For the cargo configuration, the capsule and tunnel are not required.[8]

Payload Section

The payload section is a cylindrical composite structure that contains up to 20 mt of cargo. The section is 4 meters tall with a 5.9-meter inner diameter. Door clearance is 3.75 x 5.25 meters.

During the emplacement phase, the payload section can also be separated and precisely positioned when coupled with the nose section. This is particularly useful for re-locating and positioning surface power systems and other propellant transfer equipment. This also enables ease-of-offload for much of the initial infrastructure including the delivery of key payload offloading and ground mobility systems required for the reusable Hercules used later, as depicted in Fig. 2.

Options for this offloading system include delivery of a mobile lift vehicle with a large scissors jack for lowering payloads to the surface; or a payload section mounted crane to lower payloads or crew. Additional options under consideration for the infrastructure buildup phase include either converting the initial payload sections to habitable volumes or outfitting them to serve as surface habitats.[9]

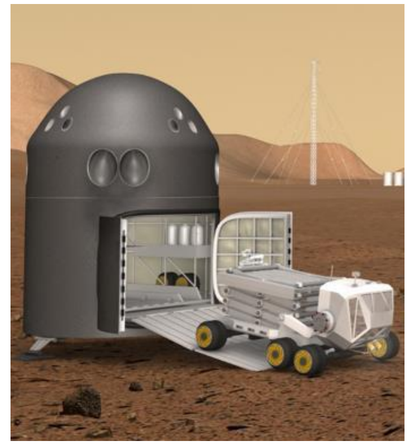

Figure 2—Simplified delivery of payloads from decoupled HSRV payload and nose section

<u>*Ascent/Descent Section*</u>

The ascent/descent section includes the ascent propellant tank and feed system; a descent propellant tank and feed system; the Ascent/Descent System (ADS) rocket engines; an aft engine bay with thrust structure; the body flap and actuation system; and the landing legs.

During emplacement, the ascent/descent section is re-positioned from the landing zone (using surface mobility systems) and re-purposed as a long-duration propellant storage facility as part of the in-situ propellant production infrastructure, as illustrated in Fig. 3. Alternative ideas for re-purposing include replacing the ascent tank system with a habitat "shell" for use on the surface. Additional subsystems and logistics delivered separately could be assembled with the habitat to form a fully functional surface habitat.

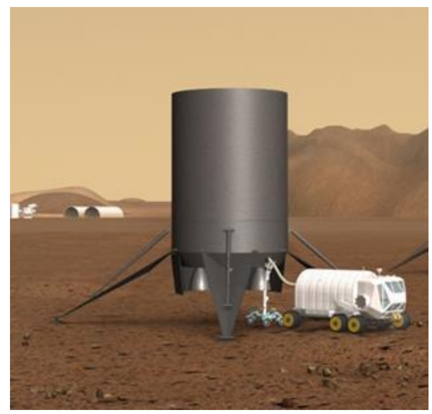

Figure 3-- Ascent/descent section emplaced as the Hercules Propellant Storage Facility (HPSF)

In the later campaign phases (*Found, Expand, and Sustain*) when the HSRV is fully reusable, the ascent/descent section is loaded with propellant manufactured at the base from Mars resources just prior to flight. This "load-and-go" resupply strategy places the burden for long-duration thermal management of cryogenic propellants on the ground system infrastructure.[10]

An example outline of the ascent/descent section systems and components in a common functional Master Equipment List (MEL) format is provided in Appendix A. This will be helpful in the early identification of operations, maintenance, and repair concepts. By addressing each of the vehicle's functions, systems, and components, this structured approach makes identification of technology choices easier.

C. Mars Surface Master Planning Assumptions

1. Siting

The Hercules concept envisions a base surface site selected for its key resources to support the development of a Mars surface settlement. For conceptual planning purposes, an Exploration Zone (EZ) is created with a diameter of 100-km. The Hercules concept explores the use of a previously identified landing site with favorable attributes; specifically, Deuteronilus Mensea. This site possesses an abundance of ice that resides close to the surface and is less susceptible to dust storms.

2. Major Functions

Conceptual layout of the base at the surface site is shown in Fig. 4. Relative placement of the various functional stations must be driven by the desire to minimize risk to the personnel and infrastructure during launch and landing operations.

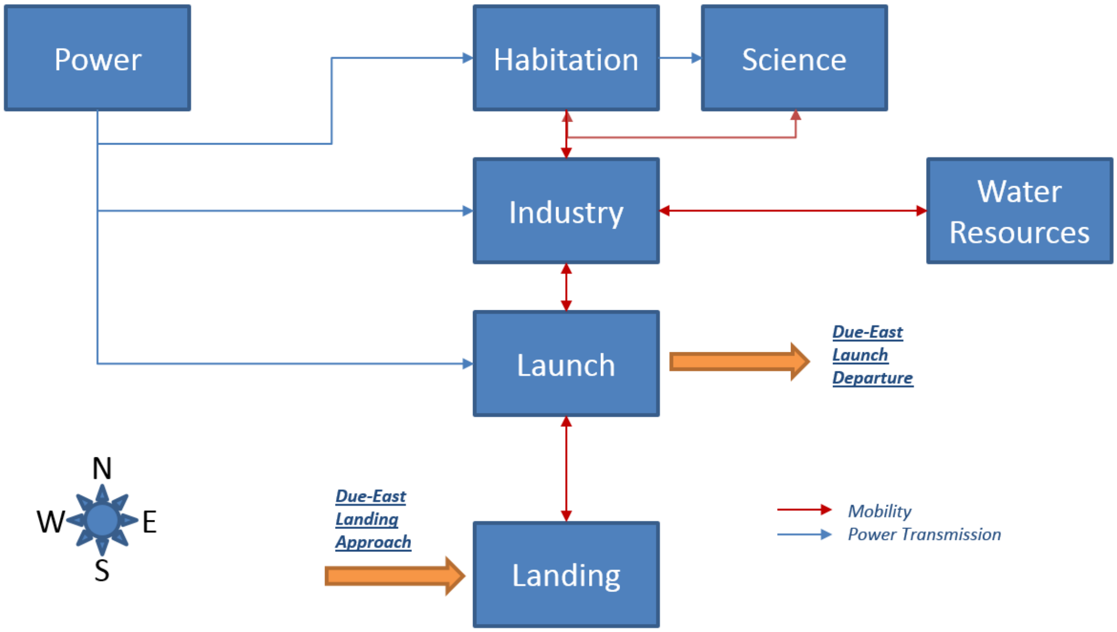

Figure 4—Initial diagram providing relationship of surface station functions at a Hercules Mars site

The HSRV's nominal operations at Mars include loading propellants produced at Mars at the surface base, launching to the LMO node to pick up cargo or crew, and landing back at the surface base to offload the cargo. In terms of the Mars surface architecture, key infrastructure required to support the HSRV operations includes surface power systems, the propellant production plant, mobile cargo offloading equipment, a launch facility, a separate landing zone, and mobility equipment that can transport the HSRV from the landing zone to the launch facility. In addition, systems for autonomous inspection and maintenance are needed to verify the integrity of the vehicle prior to launch.

The propellant production plant is located in an industrial zone adjacent to the launch facility. The plant includes fixed and mobile infrastructure for resource acquisition (water and carbon dioxide), propellant manufacturing, liquefaction, propellant storage, and propellant transfer. The entire base, including the production plant, are supported by the power system infrastructure.

Offloading cargo from the HSRV payload bay requires some form of hoist or lift that can handle the 20-ton payload in Mars gravity. For the initial flights in the Prepare phase of the campaign the HSRV is not re-used; rather, the sections of the vehicle are re-purposed to support the base infrastructure and campaign. The HSRV design allows the sections to separate and be transported by the nose section for precise positioning. For example, the first flight may deliver a nuclear power system that is located in a remote zone relative to the other base zones (i.e. - habitation, industrial, launch, and landing zones). However, the ascent and descent sections of the HSRV are re-purposed to the industrial zone to serve as a propellant storage facility. Thus, the landing will initially target a landing location to position the tanks sections, then the nose and payload sections containing the power system separate and are relocated to the power zone using the nose section mobility system.

The launch zone is located such that the ascending HSRV does not fly over any of the base zones. Ideally, the launch zone has a prepared pad that mitigates the risks associated with surface ejecta due to rocket engine plumes at engine start.

The landing zone is located 1-2 km south of the launch zone such that the arriving HSRV, coming in from the west, does not overfly the base. Despite expectations of a precision landing capability, the choice to have separate launch and landing zones is to minimize the risk to the base for a missed landing. This drives the need for mobility systems that can transport the HSRV from the landing to launch zones.

Given that the HSRV is reusable, mobile robotic systems that operate autonomously are needed to perform inspections and maintenance. Initial operations at the moon allow demonstration and development of autonomous robotic capabilities for servicing, maintenance, construction, etc…, where they can be operated semi-autonomously.

Over time, autonomy of the robotic systems is proven, thus buying down development and operational risk for the Mars campaign.

As a contingency during HSRV flight operations, an additional Hercules Crew Rescue Vehicle (HCRV) is based at the launch site, consisting of a space nose section from a previous re-purposed HSRV. Resupplied for every launch and entry event, this "surface" HCRV is on standby in the event of an abort-to-surface event by the HSRV. The HCRV is designed to have roundtrip hopping capability from the base to any point in the EZ – 50 km in any direction from the surface base – enabling crew rescue for any abort-to-surface event within the EZ.[11]

D. Hercules Operating Base Scope

Referring to Fig. 4, this analysis addresses those functions associated directly with the HSRV. It does not include the habitation, science, water resources, nor the workings of the power station(s). The industrial aspects addressed include liquefaction, propellant storage, and propellant transfer. It does not include resource extraction and propellant production. Also not addressed is a surface-based communications capability.

III. Preliminary HSRV Operating Base Systems Analysis

This section briefly summarizes the major components of this analysis. The analysis begins by identifying the goals and objectives associated with organizing and defining the Hercules operating base portion of the exploration zone.

A. Goals and Objectives of Analysis

1. *Hercules Transportation System Goals*

   Goal 1—Define a surface architecture that supports a continuous flow of crew and cargo to LMO from the assumed Mars surface site.

   Goal 2—Emplacement and setup of the surface station equipment must be done autonomously prior to risking crew operations.
2. *Systems Engineering and Analysis Goal*

   Follow NASA's Systems Engineering approach in organizing concept study products.[12] Example study products address the following:

   - Identify surface architectural development criteria consistent with Hercules Transportation System concept
   - Involve mission and vehicle analyst, along with surface systems technologists and engineers
   - Identify and begin organizing tradeoffs and surface system concept studies
   - Identify top-level surface system station sets for which requirements can be organized
   - Define top-level figures of merit that can accommodate routinely reused flight systems and allows identification of top-level technical performance measures
   - Prepare for preliminary evaluations of possible traffic models
   - Explore:
     - Hercules Operating Base justification for emplacement, construction, and operation;
     - Structured Concept of Operations (ConOps), including maintenance and support functions;
     - High-level WBSs;
     - Structured framework for cost, schedule, and risk estimates
     - Technology assessment and maturation strategies.

B. Approach to defining Surface Station and System Equipment

To begin, the concept of operations is organized by major surface support functions, such as pre-flight operations, post-flight operations, maintenance, and logistical support. These functions are confined by the scope of the analysis to only those functions directly supporting the operation and maintenance of the Hercules flight system. It does not include operation and maintenance of the habitation stations, propellant production stations, etc.

The next step in the approach is to define the support site by its sets of station equipment; i.e. *station sets*. Station sets are either geographically concentrated, or a networked capability such as power distribution, communications, or commodity distribution (liquids and gases such as water or propellant).

C. Conceptual Design Criteria and Assumptions

Each station of the operating base will require identification of the design constraints and considerations to accommode the Hercules traffic model. Ground rules and assumptions provided by the Hercules system architect are documented.[13]

IV. Functional Model of Reusable Hercules Surface Operations and Support

A. Top-Level Functions of a Mars Operating Base Supporting a Reusable Taxi Service

A top-level functional model of Hercules operations and support is in Fig. 5.

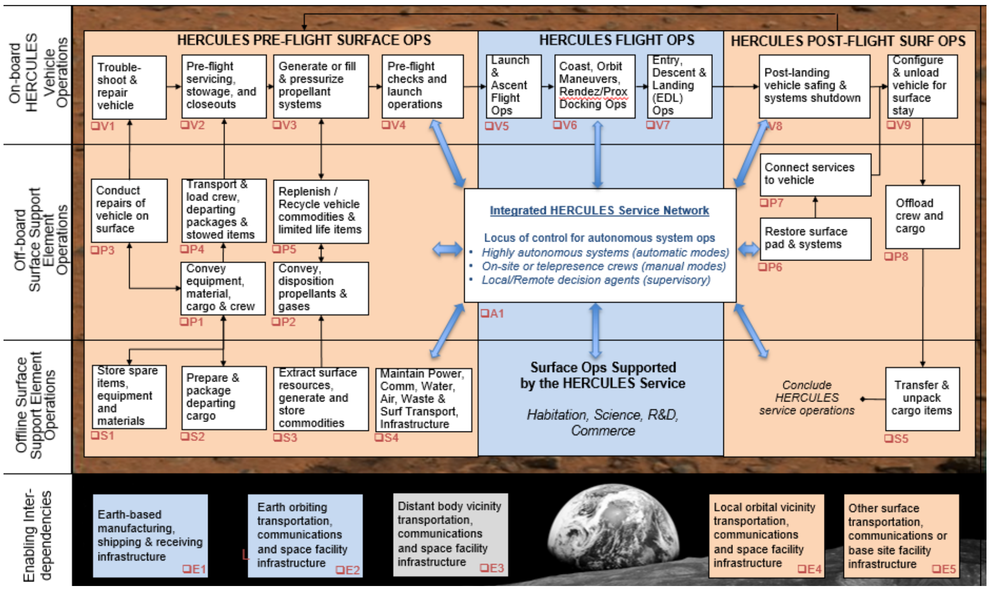

Figure 5— Reusable Hercules Taxi Service Surface Ops and Support Functional Model

B. Hercules Pre-Flight Surface Operations Functions

As an example, the Hercules pre-flight surface operations are explored and organized. Without knowing the details of the equipment designs (both flight and ground), generic functions will need to be addressed and form the basis of the concept of operations.

Hercules vehicle operations, from an on-board perspective, may involve safing of systems, shutdown, personnel and cargo transfer, power-up, propellant and gas servicing, self-test, and launch departure sequencing.

Hercules surface operations, from an off-board systems perspective, may involve connection to the vehicle of various surface-supplied services such as electrical power; water, propellants, gases, and other material commodities; loading of cargo; as well as transfer of personnel to and from the vehicle.

Hercules surface operations, from an offline surface logistics and supply-chain perspective, may involve numerous capabilities. Examples include storage of elements and parts, storage of multi-use supplies (water, gaseous nitrogen and oxygen), maintenance kits, and fabrication areas.

V. Organizing HSRV Mars Surface Support Stations and Processes

A. Online Station Examples

1. *Assembly, Loading, and Payload Handling Station Set*
    - Vehicle Handling Element(s)
    - Payload Handling Device
2. *Launch Pad*
    - Prepared Apron
    - Exhaust Bucket/Trench
    - Vibroacoustic/Thermal - Deflector

- Robotic/Personnel Access Kit

3. *Landing Pad*
    - Prepared Apron
    - Robotic/Personnel Access Kit
    - Exhaust Mitigation Kit
    - Landing Target/Aids
4. *Mobile vehicle HSRV transfer equipment*
    - ATHLETE transporter(s) – including jacking and leveling
5. *Propellant Production Facility*
    - Excavator(s)
    - Penetrators/Borers
    - Hoppers/Crushers
    - Reactor
    - Accumulator Tanks
    - Mobile Heavy Equipment/Tools Set
6. *Propellant Transfer Station Set*
    - Mobile Propellant Conditioning Facility (MPCF)
    - Hercules Propellant Storage Facility(s) (HPSF)
    - Umbilical System
    - In situ Propellant Production Facility (IPPF) Transfer Lines to HPSF(s)
    - Pad Cross Country Lines to HSRV

B. Support Station Examples

7. *Communications Station*
    - Communications Tower
    - Communications Base
    - Portable Communications Unit
    - Intercommunications Network
8. *Power Station Set*
    - Power Substation
    - Mobile Power Units
    - Power Grid
9. *Equipment storage Station*
    - Equipment Shelter (above surface)
    - Berm Protected Shelter (above surface)
    - Excavated Shelter (below surface)
    - Robotic/Personnel Access Devices
10. *Weather Station*

VI. Example Hercules Launch and Landing Station Concept Definition

A. Approach to Defining a Support Station

Fig 6 illustrates the station set approach to organizing the surface architecture. Each station contains a set of assets requiring design, fabrication, emplacement, and procedures to operate. Additionally, each station has a functional boundary through which material, energy, and information flow. Online stations directly serve the transportation elements. There may also be supporting stations to supply and maintain the operation of the online stations.

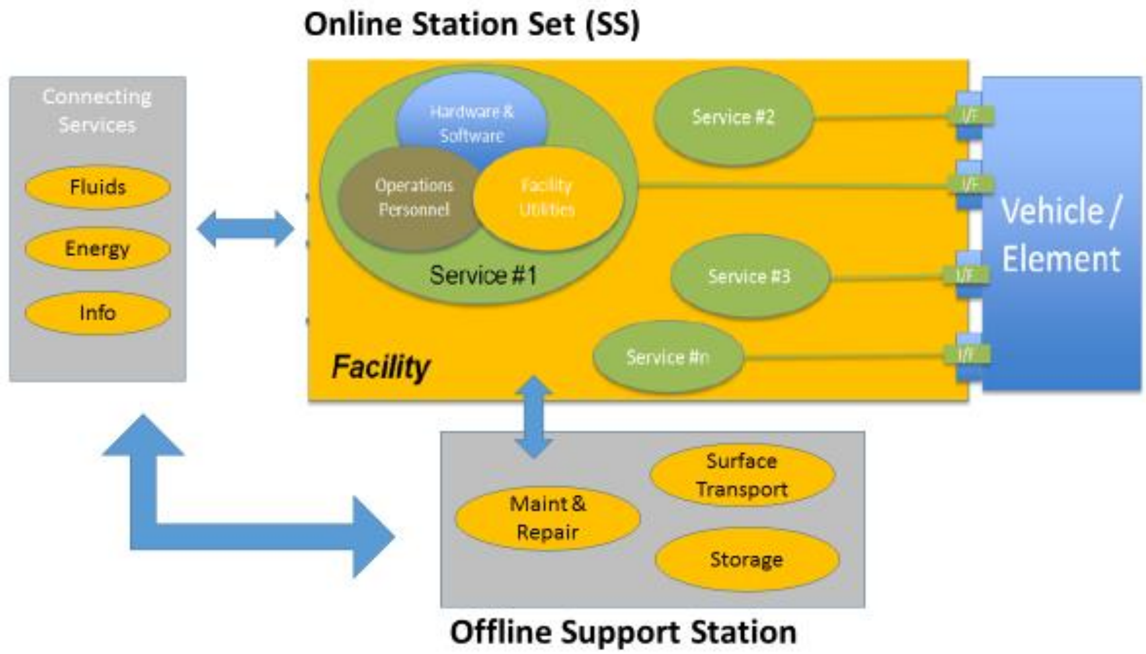

Figure 6—Station set definition process

B. Launch and Landing Station Master Planning

The master planning process begins by examination of the primary stations of interest; i.e., the launch and landing stations, since this is where the flight vehicle resides. To begin understanding the engineering criteria that drive the design of such stations, Hercules station set criteria and assumptions are documented, and can be referred to in Appendix B.[14] Hercules over-flight ground-track will drive the placement of not only the Hercules operating base stations, but also other areas of the landing zone, in particular the habitation areas. The following sections address two other technical challenges that confront the launch and landing station architect:

1. Launch and Landing Azimuths

Consideration of both the outbound and inbound paths of the Hercules vehicles, and the base layout in its operating state is required. Consideration is also required for interim equipment positions during the construction and emplacement phases.

2. Separation Distances and Blast Mitigation Techniques

The launch and landing stations, in particular, require separation from other operating stations and equipment. This is often done through a calculation of a safe *quantity distance* (QD), determined primarily by the quantity of propellant and explosive material contained. Example safe area zones for cryogenic storage sphere safe radius and blast danger areas (BDAs) are in Appendix D. This example, while Earth-based and perhaps not at the correct scale, conveys the type of site master planning needed.

Reduction of blast effects can occur for the Hercules concept if operation of the propulsion system, when in proximity to the surface for both landing and launch, uses the elevated nose section engines.

Another technique is to prepare the surface with berms. For example, a LANCE bulldozer attachment can erect a barrier at the perimeter of the landing area to block the path of ejected particles due to launch/landing.[15]

3. Autonomous Operations

Factors to consider for each surface station include those for surface-crew interaction, but also autonomous emplacement, autonomous operation, maintenance, and repair. Factors to accommodate autonomy is a subject for follow-on work.

C. Launch and Landing Station Functional Definition

Having defined the goals of the operating base, and the organization of its functional stations, the next step is to catalog and consider the functions associated with Hercules launches and landings. Top-level functions for launch include:[16]

- Provide surface access paths to and from the launch station
- Verify launch facility is on-line and functional
- Position flight vehicle for/at launch site
- Mate with facility and verify functional interfaces (if any)
- Integrate payload and/or personnel module with vehicle and verify functional interfaces (if any)
- Provide vehicle weather/environmental protection (if required)
    - Wind, rain, dust, ice, lightning, etc.
- Perform local servicing of commodities and close-out for flight if required at this station
- Perform remote servicing of commodities and close-out for flight if required at this station
- Ingress crew/passengers
- Launch the vehicle
- Reset launch facility for next use
- Service, maintain, and repair launch facility and its support systems

Top-level functions for landing include:

- Provide surface access paths to and from the landing station
- Provide utilities to vehicle at landing point (power, cooling, purging)
- Provide crew/passenger egress capability
- Provide down-cargo removal capability
- Transfer flight vehicle to next facility station at the site
- Maintain/verify landing facility and systems functional

The starting point from which these top-level functions were derived is provided in Appendix C.

D. Launch and Landing Station Concept of Operations and Support

Having defined the functions for the launch and landing station, the next step is to define the sequence of general operations functions; i.e., those functions that exist regardless of the design specifics of the facilities, equipment, and networked services. Additionally, the sequence of launch and landing functions need to relate the flight system and its subsystems. Therefore, a suggested starting point is to relate the catalog of launch and landing functions in Appendix C to a top-level master equipment list for the Hercules vehicle (similar to the Master Equipment List (MEL) in Appendix A for the HPSF).

E. Launch and Landing Station System Definition

With siting requirements, a breakdown of launch and landing station functional requirements, and a functional flow of operations and support all known, conceptual design of the launch and landing station elements, equipment, components, and subassemblies can begin.

F. Operational Timeline Development

The architect then builds a preliminary, but comprehensive task list by correlating generic operations and support functions (verbs) with specific launch and landing station assets (nouns). A timeline is constructed by connecting the various tasks through a logical network of task-to-task constraints.

G. Inspection, Repair, and Maintenance of the Launch and Landing Stations

Finally, support functions for the launch and landing stations need to address inspection, repair, and maintenance of all systems and equipment. The inclusion of designs focused on autonomous maintenance will be important.

VII. Life Cycle Assessments

A. Life Cycle Figures of Merit Mission and Market Assessments

As with all other analyses discussed, the success of the architecture as a whole requires a structured analysis approach. For the Hercules system, example figures of merit include the cumulative work effort and materials (cost) required to produce an HSRV flight, turnaround time, and annual throughput of cargo mass and personnel to and from the surface to LMO.

Each Hercules operating station design option will need to be assessed against these criteria. The lifecycle includes nonrecurring acquisition costs/schedules, and recurring operations/support phases that begin when the emplacement items arrive at the earth based departure point. It ends with the retirement of those assets at the emplaced surface site.

The financial context for these lifecycle analyses tends to come in two forms. The first is a traditional mission analysis in which a government entity conducts an end-to-end mission cycle (Mars Curiosity mission, for example), or a campaign of missions to establish a capability or accomplish a particular objective (International Space Station, for example). This mission context tends to focus on cost and system performance. In the second context, a commercial space market context, the engineering economics involve not only cost, but revenue streams as well. System Performance is also important, but balanced by factors steered by market forces and competition, and thus are more complex to analyze.

Assessing Hercules lifecycle characteristics requires first knowledge of which the two contexts applies—traditional mission and campaign analysis, or a market based context. Both contexts may apply, but in sequence; i.e., a campaign of emplacement, followed by commercial operation of various stations at the operating base. For example, there may be competing propellant production suppliers serving other stations at a growing settlement.

B. Research and Technology (R&T) Phase Assessments

Since the challenges of autonomous propellant management, in situ resource utilization, and many other undemonstrated capabilities will be required, a Research and Technology (R&T) phase is required. This R&T phase will need demonstrate viable surface support systems and technologies playing together with flight demonstrators both on the ground and in space.

C. Design and Development Phase Assessments

Once there is confidence in the technologies, design methods, and autonomous operations of multiple elements at once, commitment to design and develop Hercules systems can commence. The design and development would follow a systems engineering approach, such as that documented in NASAs Systems Engineering Handbook.

D. Launch, Transport and Emplacement Phase Assessments

Uniquely new to our systems engineering processes is the emplacement of a full service, and autonomously operated, infrastructure on the surface of another lunar-planetary body. Careful optimization of the Hercules surface support architecture is crucial to a successful emplacement, due to the mass of delivered assets and complexity of automation, among other criteria.

E. Operations and Maintenance (O&M) Phase Assessments

Since the main Hercules-concept objective is growth beyond the initially emplaced assets, the operations need to assess not only the concept of operations shown in Fig. 5, but also growth in the number of operating bases employing these concepts of operation. Additionally, the operations phase should be assessed for what it would take to manage this type of growth efficiently.

Maintenance and supply of the various stations will require a great deal of work to assess the economic impact. This is due to maintenance realities of the equipment in the Mars environment, and will necessarily introduce innovative ways to supply material and energy over time.

VIII. Summary and Conclusions

A. Summary

A systematic approach for operating base architectural definition has been explored; starting with the breakdown of the various master-planning assumptions associated with Mars Surface siting and surface element functions. By breaking down the various operations that occur in the different operating zones, a preliminary operating base systems analysis can occur in accordance with the Pre-Phase A concept studies described in the NASA systems engineering handbook. After defining the approach of the analysis, and the stated criteria and assumptions associated with the specific Hercules concept, a top-level functional model of surface operations and support could be developed, and organization of the stations and processes based around this functional model could begin. Heavy emphasis is placed on the launch and landing station for this particular concept, as it is where the flight system is located when not in use, and serves as the basis for the remainder of the surface architecture. The overall master planning of the launch and landing pad, ranging from concepts of operations to station system definition, began, and this allowed the lifecycle as a whole to be evaluated at a basic level. Figures of merit, R&T, Design and development, O&M, and launch, transport, and emplacement phase assessments were briefly discussed, and gave a picture of future trades that should be conducted on the concept.

B. Conclusions

After searching for pre-existing Mars surface siting data for human-scale transportation systems, little published information is available. Research about sustainable surface stations for safe and effective operations, particularly for reusable systems such as the Hercules concept, is needed before any advancement can be made with a concept of this complexitity.

One siting criteria observed is a one kilometer separation distance from vehicles that are power landed or alternatively vertically launch from the surface of the moon or Mars. It appears that this criterion has its basis on a preliminary analysis performed with Apollo lunar mission data. This criterion should be re-examined by Hercules architects in order to arrive at a feasible operating base layout. One method to explore is for both the launch and landing phases of the HSRV to use the nose section propulsion exclusively at or near the surface. Both a plume and ejecta analysis would help establish quantifiable separation distances required for surface site master planning. Further, by using this technique, or others, challenges associated with propellant transfer can become more manageable.[17]

Organization of a conceptual Hercules operating base by functional station sets are useful in establishing siting criteria and functional requirements for facilities, equipment, and networked services, and this paper serves as a stepping-stone for the future master planning of the Hercules concept. Further work is required to define preliminary surface element designs for each station set, but by taking the functional station set approach to conceptual design of the operating base, optimization can logically proceed to minimize the emplaced mass, the energy required, and to allow for a structured design for autonomy approach.

Autonomous system design methods and techniques were researched, and several useful projects and proposed capabilities were found. For example, Kennedy Space Center recently explored an End Effector Toolbox design approach for NASA's Game Changing Technologies Program. This toolbox approach could enable autonomous inspection, repair, and maintenance across the various Hercules operating base stations. Such a toolbox, if designed into the MPCF, HPSF, HSRV, and other Hercules system elements, is a good example of design for autonomy. Consideration of these methods and techniques, once published, can find extensive application throughout the conceptual design of all Hercules elements.

Appendix A—Example Master Equipment List for Ascent/Descent Section (repurposed as HPSF)

Functional Category	***Equipment Group***	*Component Sub-Assembly*
Body/Aero Structures		
	Primary Pressurized Structure	
		Integral Common Bulkhead (CBH) Tank – Fuel Segment (LCH4); Oxidizer Segment (LO2)
	Primary Unpressurized Structure	
		Forward Skirt, Ascent/Descent Section
		Aft Skirt, Ascent Descent Section
		Framing, Engine Thrust Structure
		Base Heat Shield
		Mounting Attachments, Landing Gear
		Mounting Attachments, Descent Propellant Tanks
Connection and Separation Systems		
	Mating Interface Mechanisms	
		Payload Section Attachments
		Payload Section – to – Ascent/Descent Section Service Feed-Through Umbilical
	Separation Mechanisms (Emplaced Elements Only)	
		Payload Section – to – Ascent/Descent Section Separation Mechanism
Launch/Takeoff & Landing Support Systems		
	Launch Support Equipment	
		None
	Landing Gear	
		Extensible Landing Gear Components (x4)
	Deployable Aerodynamic Devices	
		None
	Vertical Landing Deceleration Equipment	
		[See Nose Section Propulsion]
Natural and Induced Environment Protection		
	Radiation Protection	
		MLI(Multi-Layer Insulation)
	Micro Meteoroid & Orbital Debris Protection	
		None
	Thermal Protection	
		Tiles
		Panels
		Blankets
		Hot-Gas Seals
	Contamination Control Equipment	

		Dust Filters
Propulsion Systems		
	Main Thrust Generation Equipment	
		Gas-Generator Main Engines (x5)
	Main Propellant Management Systems	
		LO2 Feedline
		LCH4 Feedline
		Onboard LO2 Tank Pressurization Components (Pressurization Lines, Sensors, Valves, Regulators)
		Onboard LCH4 Tank Pressurization Components (Pressurization Lines, Sensors, Valves, Regulators)
		Descent Tank-to-Ascent CBH Tank Transfer Components
		Ascent CBH Tank-to-Nose Section Propulsion Transfer Components
		LO2 Fill and Drain Components
		LCH4 Fill and Drain Components
		Main Propulsion System and Engine Electronic Controls, Sensors, etc.
	Main Propellant Storage Systems	
		LO2 Descent Tank (x2)
		LCH4 Descent Tank (x2)
		Integral Ascent CBH Tank [see body structure]
Power Systems		
	Main Power Generation Equipment	
		[Externally Provided]
		Wiring Harnesses
		Sensors
Command and Data Handling Systems		
	Command Processing Equipment	
		Computer Interface Components
		Instrumentation Components
		Cabling Harnesses
Guidance, Navigation, and Control Systems		
	Control Surfaces	
		Body Flaps Structure
		Body Flap Actuation Components
		Body Flap Hinge Line Seal
	Thrust Vector Control	
		Center Engine Actuation Components
Communications and Tracking		
	Short Range/Proximity Communication Equipment	
		Antenna Equipment
		Tracking Beacon (Emplacement Landing, Site Construction)
	Audio/Visual	
		Cameras
Thermal Control Systems		

	Active Heat Collection and Transport Equipment	
		LO2 Refrigeration Components (Refrigeration Fluid Umbilical Lines, Sensors, etc.)
		LCH4 Refrigeration Components (Refrigeration Fluid Umbilical Lines, Sensors, etc.)
	Active TCS Working Fluids (Closed Loop)	
		Nitrogen
	Active Heat Generation Equipment	
		Heaters
	Active Heat Rejection Equipment	
		[Surface Radiators Externally Provided]
	Passive Heat Rejection Equipment	
		Heat Pipes [To be Traded]
	Internal Thermal Insulating Equipment	
		LCI (Layered Composite Insulation)
		Descent Tank Insulation
		Cryogenic Transfer Line Insulation
		Other Insulating Barriers, Blankets
		Onboard TCS Management System Electronics
Environmental Control Systems		
	Environmental Monitoring and Control Equipment	
		Compartment Sensors (if needed)
	Ventilation and Pressure Control Equipment	
		[Assumed to not be required due to natural inert environment]
Manipulation and Maintenance Systems		
	Robotic and Handling Equipment	
		Manipulators (to be traded for surface outfitting)
		End Effector Toolbox
	Repair and Calibration Equipment	
		(see End Effector Toolbox)

Appendix B—Preliminary Spaceport Design Constraints

1. *Launch Station*

- Exhaust Pattern Impinging onto Surface
    - Hercules assumed height is aft engine nozzle exit plane to ground
        - Assume 1 meter for bare-field takeoff
        - Assume TBD meters for elevated trench launch configuration
    - Concentrated circular impingement pattern on the surface is assumed to be:
        - ~ 6 meters
    - Resulting debris radius can be estimated as follows:
        - 1 kilometer [Metzger paper] for exhausted debris at takeoff/landing
        - Determined by explosive commodities data and QD analysis; NASA-STD-8719.12 Safety Standard for Explosives, Propellants and Pyrotechnics. Reference DoD 6055.9-STD, Department of Defense Ammunition and Explosives Safety Standards
- Exhaust bucket/trench
    - To be traded with no trench
        - Excavated trench
            - Prepared surface
            - Unprepared surface
    - Vibroacoustic/Thermal effects and mitigation
        - Effects on HSRV reusability
        - Effects on launch/landing station reusability
    - Exhaust Gas Mitigation
        - External deflection, suppression, or mitigation required, or raise height
        - Trench or no trench? (not considering elevated launch stand)
- Prepared or unprepared surface
- Minimum height between vehicle exhaust plane and surface needs to factor debris impact (if surface not prepared)
- Assumption: Exhaust characteristics assumed to be LOX-Methane
- Distance between stored propellant stations, for example Hercules Propellant Storage Facilities 1 and 2 (HPSF 1 and 2) and launch point
- Distance between IPPF and launch point

For this example, two cases will be examined. The first case will be a simple flat surface, and the second case will use an excavated flame trench. The first case will also look at unprepared and prepared flat surfaces.

2. *Pros and Cons of Flat Case vs Excavated Flame Trench Approaches*

- Case 1a: Unprepared flat surface
    - Pros:
        - No setup required
        - Can implement early
    - Cons:
        - Debris ejecta issues
        - Uneven surface
- Case 1b: Unprepared flat surface with berms
    - Pros:
        - Minor setup required
        - Can implement relatively early
    - Cons:
        - Requires re-preparation and maintenance

- Case 2: Prepared excavated and prepared flame trench
    - Pros:
        - Easier on HSRV for repeated use
        - More suitable for sustained systems such as Hercules
        - Implementation more suitable to Hercules timeframe at Mars
    - Cons:
        - Requires significant setup

Case 1a will not be considered for Hercules (more applicable for initial landing points). Case 1b is assumed likely for initial Hercules system emplacement operations. A combination of Case 1b and Case 2 is assumed for the longer-term operational case. An example concept similar to Case 1b is found in [Mueller and King]. (get permission to put image in)

3. *Landing Station*

- How large of a pad is necessary?
    - Assuming a landing area requiring three landing points: primary (full stack), secondary (payload bay/nose sections for payload drop-off), tertiary (nose section only)
    - Require minimum distance calculations between primary to secondary landing points, and secondary to tertiary landing points
- Exhaust Pattern Impinging onto surface
    - For Hercules assumed height is nose section to ground
        - Assume 20.2 meters
    - Concentric impingement pattern on the surface is defined in a figure TBD
    - Resulting debris radius is TBD
- Minimum height between vehicle exhaust plane and surface
    - Assume 1 meter
- Assumption: Exhaust characteristics assumed to be LOX-Methane

4. *Propellant Storage and Transfer Stations*

- Siting distance from launch and landing stations
- Siting distance between landed/emplaced HPSF elements
- Siting distance to propellant production station

5. *Habitation Station*

- What is the minimum safe distance the habitation area needs to be from the launch/landing complex?
- Need to determine method of transport of HERCULES payloads from primary, secondary, and tertiary landing points to habitation area
- Define what load cases are for element transport in and out of launch/landing area
- Load capacity of transporter/carrier – ATHLETE?
- Nature of the transport path (prepared/unprepared/etc.)

6. *HERCULES turnaround function-siting considerations*

- Where will vehicle be processed between flights, landing point or launch point?
- Vehicle safing (assume landing point if any required)
- Vehicle assembly of elements (none assumed for Hercules)
- Autonomous vehicle inspection, maintenance, repair?
- Autonomous payload installation?
- Crew boarding (assume launch point)
- Propellant loading/final launch preps (assume launch point)

7. *Power Station*

- Location of power assets
    - Minimum separation distance between launch/landing zones and power assets
    - Buried?

- How much power will be needed to power all systems at all stations?
- How far away will power production be from pad/habitat areas?
- Nature of the distribution of power
    - Wireless or cabled?
- Expansion of power capacity and expansion of grid coverage
- Does the facility need to be kept separate from PPF or habitat area?
- Dedicated power to HERCULES taxi service?

8. *Communication Station*

- Location of Comm assets
    - Minimum separation distance between launch/landing zones and communication assets
    - Buried?
- Will comm be part of the habitat area, or separate facility?
- How far away does comm facility need to be from pad

9. *Surface Support Equipment Offline Maintenance and Storage Station*

- Local launch/landing pad storage vs remote storage
- Where? What is the minimum distance? Buried?
- Will there need to be multiple equipment storage facilities?
- How is the equipment moved?
    - Self-transported? Hauled? Carried? Flown?

Appendix C—Top-Level Vertical Launch Functions Sub-List

- *3.1 Top-Level Vertical Launch Functions Sub-List (each item expanded below):*
  - Verify launch facility on-line and functional
  - Position flight vehicle for/at launch site
  - Mate with facility and verify functional interfaces (if any)
  - Integrate payload and/or personnel module with vehicle and verify functional
- *Interfaces (if any)*
  - Provide vehicle weather protection (if required)
- *Wind, rain, ice, lightning, etc.*
  - Perform local servicing of commodities and close-out for flight if required at this module
  - Perform remote servicing of commodities and close-out for flight if required at this module
  - Ingress crew/passengers
  - Launch the vehicle
  - Recycle/ refurbish launch facility
  - Service launch facility support systems

- *3.1 Top-Level Vertical Launch Functions*
  - Verify launch facility on-line and functional
    - Verify electrical power systems functional
    - Verify pad communications systems functional (OIS, OTV, paging/ warning,
  - hazardous gas detection/ alarm systems)
    - Verify command and control systems functional
    - Verify propellants and gasses storage and transfer systems functional
    - Verify access and handling systems functional (elevators, cranes, safety
  - doors, payload-unique handling equipment, weather protection, etc.)
    - Verify industrial water systems functional (tower/pad deluge, flame deflector, deluge, sound suppression, ignition overpressure, etc.)
    - Verify fire-ex emergency water systems functional

  - Position flight vehicle for/at launch site
    - Transport vehicle to launch pad
    - Position and align for erection (if required)
    - Erect to vertical (if required)
    - Verify position and alignment
    - Remove transportation/ erection hardware (if required)

  - Mate with facility and verify functional interfaces (if any)
    - Install/ mate electrical power umbilicals to vehicle and verify all conductor continuity and free of short circuits (if required)
    - Install/ mate communications/ data umbilicals to vehicle and verify functional signal strength and noise levels if required (fiber optics, copper path, etc)
    - Verify RF/ IR communication paths functional between vehicle and facility
    - Position access systems/ equipment required (swing arms, access platforms and hardware protective kits, etc)
    - Structurally mate vehicle to facility and torque fasteners (explosive bolts) for hold-down, umbilical carrier plates, and stabilizers, if required
    - Remove any temporary structural supports if required
    - If vehicle was mated to launcher (mobile platform) at prior module, mate/install launcher to facility and structurally attach to supports
    - Install/ mate cryogenic fluid umbilicals and leak check (if required)
    - Install/ mate toxic fluid umbilicals and leak check (NH3, MMH, N2O4, etc)
    - Install/ mate non-toxic storable liquids umbilicals and leak check (RP-1, alcohol, hydraulic fluid, coolants, H2O2, water, etc., if required)
    - Install/ mate gaseous umbilicals and leak check (GN2, GHe, GH2, GO2, air, etc.)

- Integrate payload and/or personnel module with vehicle and verify functional interfaces (if any)
    - Perform cargo removal if desired
    - Provide access to payload
    - Position and connect handling equipment
    - Demate payload from vehicle
    - Remove payload, place on transporter and establish required services
    - Remove payload-unique accommodations from vehicle
    - Install cargo if desired
    - Configure vehicle and install payload-unique accommodations
    - Clean/ verify vehicle cleanliness if required
    - Position, and install handling equipment on payload
    - Install payload
    - Mate payload-to-vehicle interfaces and verify functional

- Provide vehicle environmental protection (if required)
    - Position wind/ rain/ hail/ snow protection systems
    - Position/ check electrical continuity of lightning-sensing and protection system
    - Provide/ position vehicle thermal management and control system if used

- Perform local servicing of commodities and close-out for flight if required at this module
    - Drain and flush fluid systems as required
    - Replenish, fill or verify fluids and gasses commodities, and verify chemical purity at desired level (if appropriate at this module)
    - Recharge batteries or replace if needed
    - Lubricate and adjust subsystems as required
    - Install ordnance if desired
    - Perform flight and ground systems ordnance installation operations (if required in this module)
    - Establish RF silence (includes no-switching)
    - Remove spent ordnance and install and install new end items
    - Verify stray voltage control
    - Perform electrical mate and configure safe & arm devices
    - Perform range safety interface command checks
    - Verify functional links with space-based assets (if incorporated)
    - Perform any needed cleaning before close-out
    - Remove any access hardware or other non-flight hardware
    - Perform close-out photography if desires
    - Install close-out covers and access doors and leak check as required

- Perform remote servicing of commodities and close-out for flight if required at this module
    - Clear personnel from pad-blast danger area
    - Load main propellants for flight (cryogenic and high-pressure gasses to flight pressure)
    - Establish steady-state replenish of cryos
- Ingress crew/passengers
    - Prepare crew/ passenger module for ingress
    - Transport personnel to pad for ingress (boarding)
    - Prepare and board flight personnel (flight suits, security/ badge/ identification checks, etc.)
    - Stow carry-on items
    - Seat/ secure personnel for launch/ flight environment
    - Close access hatch/ door and remove/ stow access equipment

        - Transport ground service crew to fall-back area

    - Launch the vehicle
        - Verify vehicle and environment ready for launch
        - Ground support personnel fall-back complete
        - Emergency fire and medical equipment and personnel on station
        - Obtain clearances to launch/ fly (if appropriate)
        - Execute auto launch sequence
        - Provide emergency abort flight personnel egress capability

    - Recycle/ refurbish launch facility
        - Secure/ safe ground systems (reactivate pre-launch-secured utilities [electrical power, lighting, fire alarms, HVAC, potable water, communications, etc], drain and purge propellant transfer systems, vent and purge high-pressure peumatics systems, safe high-volume low-pressure facility purge systems, safe ordnance systems, replace personnel restraint systems [safety railing etc])
        - Perform facilities and systems walk-down inspections and document anomalies for repair/ refurb cycle
        - Schedule and perform repair/ refurbish of systems
        - Perform pad washdown if required
        - Remove/ treat contaminated fluids (water/ acid, etc) and transport for disposal
        - Repair vehicle-exhaust deflectors if deteriorated
        - Transport mobile launch structures/ platform to appropriate module
        - Perform systems/ structures preventive maintenance as scheduled
        - Verify facilities and systems functional for next launch

    - Service launch facility support systems
        - Replenish liquids and gasses commodities for next launch
        - Service safety, fire and emergency equipment as required An appendix, if needed, should appear before the acknowledgements.

- *LANDING/RECOVERY FACILITIES MODULE*

- *TOP-LEVEL FUNCTIONS LIST (each item expanded below):*
    - Provide utilities to vehicle at motion-stop (power, cooling, purging)
    - Provide crew/passenger egress capability
    - Provide down-cargo removal capability
    - Transfer flight vehicle to next facility in flow
    - Maintain/ verify landing facility and systems functional
    - Provide support-aircraft fueling capability
    - Provide utilities to vehicle at motion-stop (power, cooling, purging)
        - Coordinate vehicle safeing and application of ground-supplied services as required
            - If required, check for toxic vapor leakage and take corrective action as needed: Quantity of leakage test sites on vehicle:
                - Potential toxic vapor leak sites
                - Pull samples of gas from hazardous gas detection system lines and verify no abnormal leakage and safe to start post-landing purge(s)
                - Vent pressure vessels to safe post-landing level if required:
                - Position/ mate mobile ground support equipment (GSE) and verify interface
                - Connect electrical/static ground to vehicle and verify less than one ohm
                - Chock wheels or insert landing gear pins

- Position GSE for mate to vehicle
- Provide access for umbilical(s) mate: Quantity of umbilical carrier plates required for post-landing ground service:
- Provide cryo vent and drain as required for vehicle safety
- Connect purge, vent, and drain ground lines to vehicle

Appendix D—Example Cryogenic Storage Sphere Safe Radius and Blast Danger Area Charts

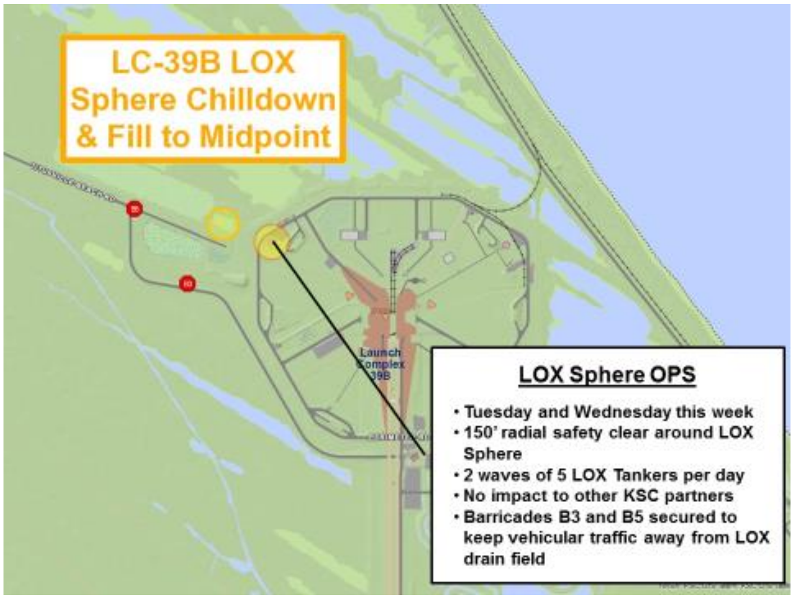

Figure 7—Cryogenic Storage Sphere Safe Radius [Image courtesy of NASA Kennedy Space Center]

Figure 8—Example Blast Danger Area [Image courtesy of NASA Kennedy Space Center]

Acknowledgments

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