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In-Space Assembly -Servicing Requirements

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Abstract

A method for developing the requirements for in-space assembly, servicing, and checkout of proposed Mars space transfer vehicles is discussed. Required in-space operations and functions are identified in relation to various Earth to Orbit (ETO) vehicles by looking at the manifesting options of baseline Mars Space Transfer Vehicles (STV). Each operation is then reduced to a minimum complexity state resulting in a set of operational primitive functions. These primitive functions are used to assess the trade-offs between robotic, telerobotic, and EVA operations. The study demonstrates that the complexity of the in-space operations remains stable with ETO vehicle size, and therefore the functions, and ultimately the infrastructure required to support proposed missions, are relatively unaffected by varying the ETO vehicle size within the range considered for this study.

Background

In undertaking a study of this or any other issue the first question which needs to be asked is, why do the study at all? In the area of in-space assembly/servicing requirements, several compelling reasons exist. The first is that the ability to live and work in space is essential to the future of NASA. In-space operations are an inherent part of all spacecraft mission scenarios. In generic form in-space operations consists of all activity that takes place between launch from the earth and landing back on earth or on another planet. Assembling and servicing operations are only subcategories of the overall in-space operations picture. The ability to assemble proposed spacecraft, and provide essential servicing during a mission is a critical aspect of mission success. The current baseline Mars STV is a case in point. Current estimates indicate that seven launches will be required to place all of the propellent and hardware in orbit, with over of fifteen months elapsing between the first and last launch. During this period of time the hardware components must be assembled, stored, maintained, and inspected. Systems must be available to provide power, communicate status, provide thermal control, inspect, assemble, manipulate, maneuver, and calibrate the vehicle. Failure to understand the technologies and the systems required to carryout these operations will have a direct impact on the safety of the crew, their ability to carry out a successful mission, and the total life cycle mission cost.

The second reason to undertake such a study is the need to understand operations early in the mission design process. In an era of tight budgets, and high expectations from the administration, the congress,

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and the public, NASA cannot afford to wait until the later stages of mission planning to consider the impact of operations at the detail level. A look at our current space transportation system underscores this point. The orbiter was designed to achieve a given performance level, with support operations being developed later in the program to fit the vehicle design. As a result of this approach extensive rework, refurbishment, and/or replacement is required between each launch. The development of a detailed support operations scenario as an integral part of the vehicle design process would have identified some of the labor intensive limitations imposed by the design, and resulted in simpler, more efficient methods for achieving the original design intent which was assured access to space. Some of the current operations and servicing requirements for mating the orbiter to the external tank could not be carried out in space with the present design. However, the functions which are carried out by these operations must necessarily be performed in space to mate vehicle components to propellent tanks. If we fail to consider the requirements that each necessary function or operation places on the design of the vehicle, we will quickly drive total mission cost to unacceptable levels, and jeopardize NASA's commitment to total quality throughout mission life.

The third reason for considering operations at this point is that we in NASA, in the early days after Apollo, made a promise to the public in return for their enthusiasm, excitement and support. That promise was that we, as a nation, would learn to live and work in space. Based on current talk within the agency in general, and within the Space Exploration Initiative (SEI) office in particular, doubts are raised as to whether we still believe we can achieve the promise. We owe the public a clear answer, not only to decide for ourselves if we can still keep the promise, but to also inform the public of the level of activity which will be necessary to achieve the promise if we believe we can do so.

Introduction

The primary objective of the study was to approach the issue of requirements from a systematic viewpoint. We did not start with a list of what we thought might be nice, nor did we start from a platform or waystation concept and work backwards to decide what we could do with the systems that were available. We started by determining what needed to be accomplished. The expected output was a list of top level requirements generated from the operations which were dictated by vehicle design, ETO limitations, and ground based integration capability. In addition we attempted to determine the minimum manpower which would be required to carry out the operations using robotics, telerobotics, or EVA. We attempted to hold to the legacy expressed in the Synthesis Report[1] of "ensuring optimum use of man-in-the-loop". As the report stated "Don't burden man if a machine can do it as well or better, and vice versa". Going into the study we neither required or eliminated any method of carrying out the operations.

The approach taken for the study was to first understand current thinking on the Space Exploration Initiative (SEI) strategy and options. We then selected a baseline Mars STV and launch vehicle. Because of the options which were being developed with respect to Heavy Lift Launch Vehicles (HLLV) we decided to carry both a 150 metric tonne and a 250 metric tonne vehicle through the study. There was a clear understanding that both the ETO vehicle and the Mars STV would change as the program evolves. However, sufficient thought had been given to current concepts that all of the necessary ingredients are included, and any changes would have little impact on the top level operations which would be required.

Use was then made of information developed under an Infrastructure Study[2] led by the Marshall Space Flight Center (MSFC), with participation by the Langley Research Center (LaRC), the Stennis Space Center (SSC), the Kennedy Space Center (KSC), and the Lewis Research Center (LeRC). This study manifested the baseline Mars STV on both 150 tonne and 250 tonne vehicles. In addition, the study looked at the trade-offs which would be required, because of the manifest, on both ground based and in-space operations. By making use of these trade-offs we were able to develop a top level operational scenario detailing the steps which must take place in space. Basic functions, and ultimately functional primitives, were generated from this operational scenario for in-space assembly of the Mars STV. These basic functions allowed generation of hardware systems and subsystems necessary to perform the functions. We then looked at both the functional primitives and the hardware systems and subsystems to make a determination of whether EVA or robotic techniques were best suited to the activity. These systems and subsystems became the requirements for any in-space infrastructure which will be used to carry out the goal of learning to live and work in space.

SEI Mission Options

Three potential mission options have been suggested for vehicle integration for the SEI program as follows:

- Direct launch of fully integrated vehicles
- Rendezvous and docking in LEO with preintegrated components
- Assemble in space

Direct launch of fully integrated vehicles imposes severe limitations on the design of the STV, and the mission duration, due to the volume constraints of the ETO launch vehicle shroud, and the initial mass in low earth orbit (IMLEO) capability.

For purposed of this study we have defined rendezvous and docking as involving no more than two launches to low earth orbit with most hardware integration being performed on the ground. Two major components would be placed in LEO by separate launches and would be joined in orbit by automated latching techniques.

In-space assembly has been defined as involving multiple launches. Preintegration of large complex components would still be accomplished on the ground. However, major system and subsystem integration would be performed in space.

Current SEI mission strategy calls for both piloted and cargo lunar missions to be completed using the direct launch of fully integrated vehicles if possible. Rendezvous and docking would be used if sufficient HLLV capability has not been developed by the mission need date. Mars STV's present a different problem. Although the cargo vehicle could be broken into two major components which allows utilization of

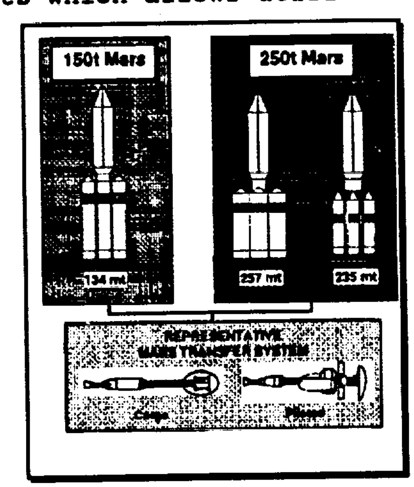

Figure 1: ETO Vehicle Classes

rendezvous and docking techniques, the mass and volume requirements of the piloted vehicle dictates that in-space assembly be performed. Figure 1 shows both the 150 tonne and 250 tonne classes of ETO vehicles which were considered in the reference 2 Infrastructure Study.

Assumptions

The following assumptions were made prior to the start of the study:

- The components that were determined to be required for an in-space infrastructure would be available as required.
- Enabling technologies would be developed to a sufficient level and in sufficient time to be incorporated into required systems as needed.
- Current technology and the advances which we expect to achieve over the next decade make telerobotic operation more practical than autonomous operation. Therefore, telerobotics would be considered as the first alternative to EVA operations.
- All hardware components would be inspected upon arrival on orbit.
- All components would be secured to the launch structure with remotely activated latches.
- The launch vehicle/structure would be capable of rendezvous with the infrastructure.
- Space Station Freedom (SSF) would be operational during the advance development phase of any program for infrastructure development.
- Launch centers would be determined by KSC based on ground processing requirements, and resource availability.
- The baseline Mars STV would be the 2016 reference NERVA derivative Nuclear Thermal Rocket (NTR) propulsion concept, defined by Boeing Defense and Space Group in their Phase I Space Transfer Concepts final report[3] to MSFC in March 1991.

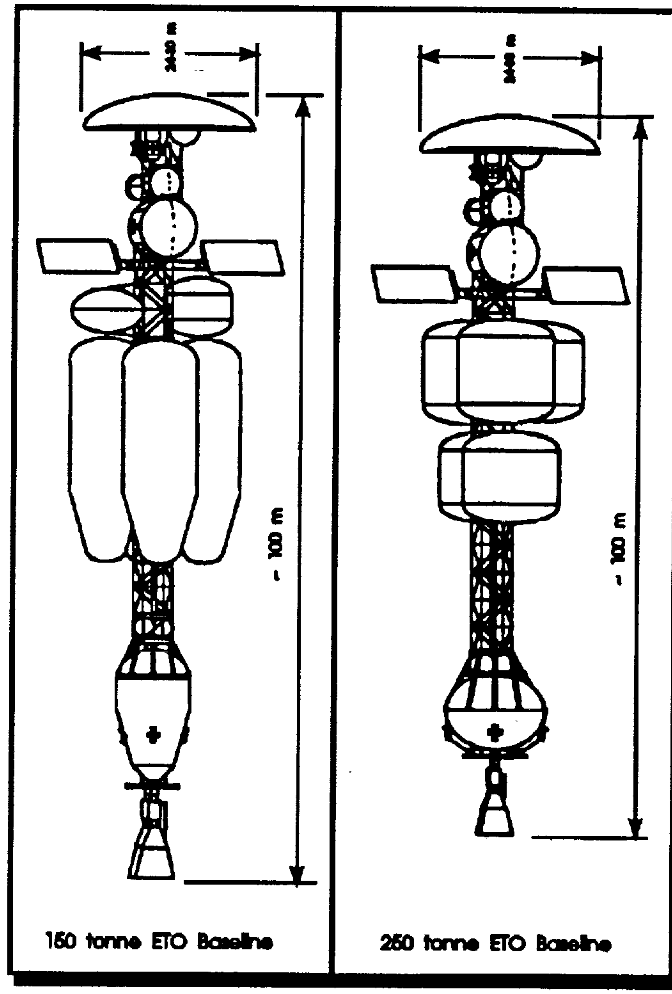

Figure 2: Mars STV Baseline Concepts

Discussion

During the reference 2 Infrastructure Study the baseline Mars STV was modified with different size propellent tanks for a 250 tonne ETO vehicle so that it would more effectively utilize the volume and IMLEO capability of the larger launch vehicle. Figure 2 shows the Mars STV concepts for each class of ETO vehicle considered.

The baseline Mars STV has a mass of 735,190 Kg which includes 525 tonnes of propellant and 92 tonnes of inert mass for the propulsion system. Figure 3 shows the baseline vehicle manifesting on a 150 tonne ETO vehicle as developed in the reference 2 infrastructure study. Figure 4 provides the same

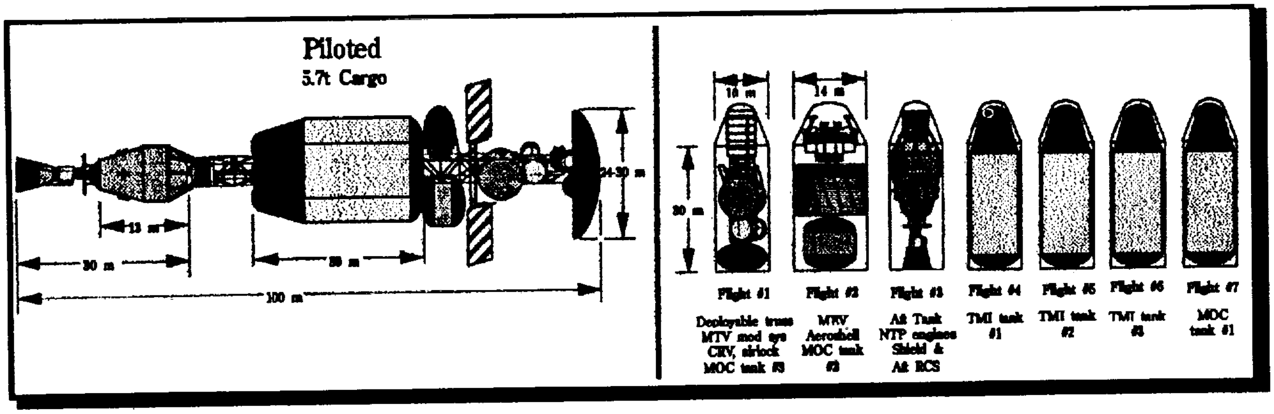

Figure 3: 150t ETO Vehicle Manifesting

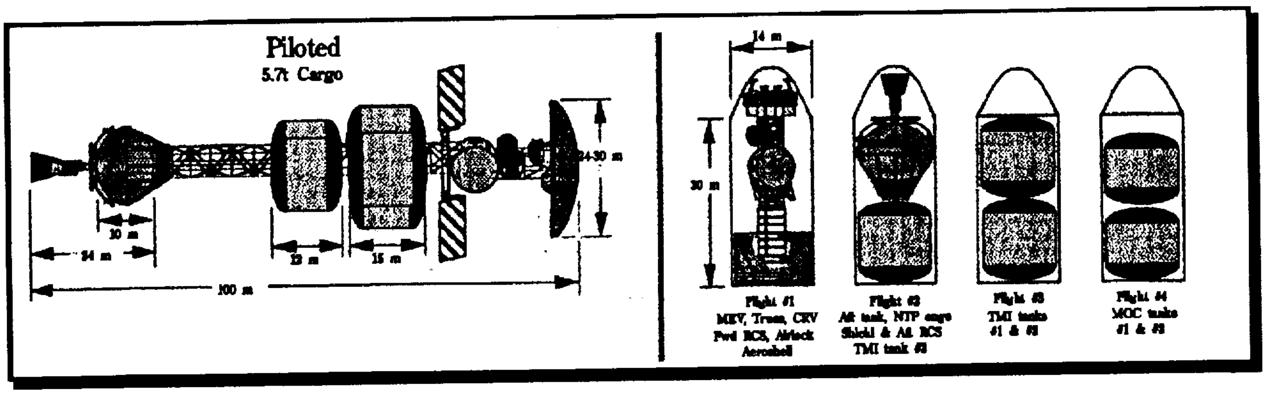

Figure 4: 250t ETO Vehicle Manifesting

information for the Mars STV as it was modified for a 250 tonne ETO vehicle.

Impact of Ground Based Operations

Recent in-house studies performed at KSC[4] reviewed the launch facilities and ground based operational requirements which would be imposed by a National Launch System (NLS). These studies identified a 150 tonne HLLV which could be used to launch the Mars STV. The HLLV ground processing time was determined to be 79 days between launches. Because of the constraints of other operations at KSC it was assumed that serial processing of the Mars STV launch vehicles would be required. This serial processing, along with the 79 day ground processing time, results in a total of 474 days between the time that the components included in the first launch arrive on orbit, and the time that the components from the seventh launch are available for assembly. Since MOC tank #3 is manifested on the first launch, cryogenic hydrogen boil-off must be considered as a part of the fuel management functions which are identified in the study.

Results

Once the manifesting of the baseline Mars STV's had been completed, a top level operational scenario was developed. This scenario looked at the major operations which would be necessary to accept, on orbit, the components from each launch and then assemble, mate, store, and maintain these components until the vehicle integration was completed. The completed state was defined to be, when all of the components, propellent, and expendable had been assembled and/or loaded on board the Mars STV, and the vehicle had been fully checked out and prepared for engine firing for trans Mars injection (TMI). This included transfer of the crew for final checkout and verification functions.

The operational scenarios for the first two launches, for both a 150 tonne ETO vehicle and a 250 tonne ETO vehicle are as follows:

Operational Scenario for 150 tonne ETO Vehicle:

Launch # 1
- Activate Communications / Power Systems
- Checkout / Calibrate On-Board Inspection Systems
- Inspect Components / Verify Health after Launch
- Demate MOC tank #3 from Launch Structure
- Maneuver MOC tank #3 to Storage / Berth Location
- Demate Remaining Components from Launch Structure
- Deploy Truss Structure
- Verify Truss is Locked in Deployed Configuration
- Activate Monitoring System
- Manage STV Attitude for Thermal Control
- Provide Debris Protection

Launch # 2
- Receive, Rendezvous, Dock Components from Second Launch
- Checkout On-Board Health Monitoring Systems
- Inspect Components / Verify Health
- Demate MEV from Launch Structure
- Maneuver and Attach MEV to Truss Structure
- Demate Aeroshell from Launch Structure
- Deploy Aeroshell
- Inspect Aeroshell Joints and Seals
- Repair, Reseal TPS Joints as Required
- Provide Inspection / Verification Data to Mission Control
- Demate MOC tank #2 from Launch Structure
- Manipulate MOC tank #2 into Position
- Attach MOC tank #2 to Truss Structure
- Unberth and Manipulate MOC tank #3 into Position
- Attach MOC tank #3 to STV Truss Structure
- Verify All Joint Connections
- Make All Utility (Communication/Power/Health) Connections
- Make Fuel Connections between MOC tank #2 & Manifold
- Perform Fuel Connection Leak Check

Operational Scenario for 250 tonne ETO Vehicle:

Launch # 1
- Activate Communication / Power Systems
- Checkout / Calibrate On-Board Inspection Systems
- Inspect Components / Verify Health After Launch
- Demate Components from Launch Structure
- Maneuver and Berth Aeroshell / Launch Structure
- Deploy Truss Structure
- Verify Truss is Locked in Deployed Configuration
- Demate Aeroshell from Berth / Launch Structure
- Deploy Aeroshell
- Attach Aeroshell to Truss and Inspect Joints / Seals
- Repair/Reseal Joints as Required
- Provide Lighting for Remote Inspection
- Provide Inspection / Verification Data to Mission Control
- Activate Large Space Structure Control System
- Manage STV Attitude for Thermal Control
- Provide Debris Protection

Launch # 2
- Receive, Rendezvous, Dock Components from Second Launch
- Checkout On-Board Health Monitoring Systems
- Demate Components from Launch Structure
- Inspect Components / Verify Health
- Maneuver and Berth TMI tank #3
- Demate Aft Components from Launch Structure
- Maneuver Aft Components into Position
- Attach Aft Components to Truss Structure

- Verify Joint Connections
- Make Utility (Communication, Power, Health) Connections
- Unberth and Manipulate TMI tank #3 into Position
- Attach TMI tank #3 to STV Assembly
- Make Fuel Connections between TMI tank #3 and Manifold
- Perform Fuel Connection Leak Check

During the study it was determined that all of the operations which are necessary to bring the Mars STV to a fully integrated condition occurred during the first two ETO launches. After the operations listed for the second launch have taken place for both ETO vehicle options, we began to repeat the operations of maneuvering, attaching, receiving, manipulating, testing, etc.. For the remaining launches no new operations were identified. This led to the development of a list of basic operational functions which are repeated during the assembly and servicing phase of Mars STV deployment. These basic functions are as follows.

Basic Operational Functions

- Deploy & Erect Structure
- Attach & (dis) Assemble Components
- Inspect Structure & Components
- (re) Calibrate Systems & Components
- Receive, Rendezvous & Dock Components
- Checkout Systems & Subsystems
- Berth & Store Components
- Maneuver Components into Position
- Manipulate Structures & Components
- Test & Verify Assemblies & Components
- Make Utility Connections
- Provide Effective Lighting
- Communicate
- Generate & Store Power
- Control Large Space Structures
- Provide Thermal & Radiation Protection
- Provide Debris Protection
- Manage Cryo Fuel Transfer & Storage
- Manage Mission Data
- Provide Support for Contingency Operations

During the study it also became clear that we could address the operational functions in two different ways. First, we could break the operational functions into several categories such as contingency support operations, operational support, and mission functional primitives. Second, we could use the operational functions to define the systems which make up the top level requirements for an in-space infrastructure which would be required for on-orbit integration of the Mars STV's.

Operational Categories

This first method of addressing the functions demonstrates the interdependencies and interrelationships of the various operational functions in each of the categories, with the primitives being used to determine the optimum method of carrying out each of the functions.

The contingency support operations make use of most of the infrastructure systems, but come into play only when normal operational functions are out of tolerance, or when the crew is arriving. As an example component change out would occur only when an individual system failed to function during in-space verification, or if a system had been damaged during operation. The self correcting capability would be utilized if a component did not fit as planned, or if alignment problems were encountered because of tolerance buildup or thermal changes to the structure. These examples also point out the need for early consideration of the in-space operations. Any problem which might call on the contingency support functions needs to be considered during the design process.

The operational support functions are those which primarily involve control of the infrastructure and its activities, or provide support to the functional primitives in carrying out the primary mission of the infrastructure.

The third category includes those functions which are necessary to complete the primary mission of an infrastructure, which is to assemble and service a Mars STV. These are the activities which require direct intervention by EVA, robotic, or telerobotic techniques. Functions in this category have been reduced to a set of functional primitives. The reduction in this manner is not intended to indicate ease of carrying out the function. In fact, just the opposite can be true. Some of the assembly and servicing activities can involve many of the functional primitives which, when combined, can become very difficult operations. The primitive functions can themselves be further reduced to a set of very difficult operations on a detail level. Also some of the operations which require reasonable simple application of the primitive functions can become very difficult due to the nature of the component being acted on. For example the act of moving the TMI tanks into position for attachment to the truss structure involves simple actions. However, when the tanks are nearly full of hydrogen propellent, in a zero gravity environment, any movement of the tank can cause a shifting of the hydrogen propellent setting up a dynamic oscillation which must be damped out. In this case an operation which involves simple functions becomes very difficult to carry out.

The basic operational functions in each of the three categories are listed below:

Contingency Support Operations:

Component Changeout
Tool Storage
Capture & Retrieval
Self Correcting Capability
Assist with Crew Transfer

Operational Support:

Lighting
Communication
Power Generation
Power Storage
Facility Control & Monitoring

Data Management
Component Storage / Berthing

Mission Functional Primitives:

Acquire	Rotate
Attach	Transport
Maneuver	Verify
Manipulate	Withdraw
Berth	Test
Inspect	Operate
Install	Insert

These mission functional primitives are activities which are ideally suited to advance telerobotic operation. Independent studies[6] have looked at the timelines which would result from using EVA, IVA and telerobotic operations. These studies indicate that total elapsed processing time would increase by 62% if the operations were performed telerobotically from the ground instead of using EVA. However, the operations can easily be performed telerobotically from the ground within the 79 day launch center for the HLLV. Total life cycle cost would decrease dramatically by using telerobotic operations. The only activity occurring on-board an infrastructure between launches is assembly and servicing functions, or station keeping. There would be no impact if assembly time were doubled or tripled over what would be required by EVA activity so long as the activity could be carried out prior to the next launch. The studies indicate that even with the increased time for telerobotic operations the majority of the time between launches would still be spent in a station keeping mode.

Functions/System Matrix

The second method of addressing the basic operational functions results in an extensive matrix which relates each of the functions to the systems and subsystems which are necessary to perform the functions. This matrix is shown in tables 1a through 1d. Each of the systems or subsystems listed directly serves at least one of the functions, or there is some connectivity between the system/subsystem and the function. An iterative process was employed in developing the matrix. First, the systems which were directly requiredle for performing a function were listed. Each system was then reevaluated against every other function to determine if there was any connectivity to the other functions. In other words, although a function did not require a specific system to perform the activity, could that activity be enhanced by using systems that are necessary to carry out some other function?

The resulting systems/subsystems become the top level requirements for an in-space infrastructure to support the assembly and servicing of a Mars STV. The requirements are independent of any current infrastructure concept. They provide a basis for evaluating concepts as to their ability to carryout required operations. These top level infrastructure system requirements are listed below:

Required Systems

- Structural for supporting the other systems
- Robotic Manipulators for assembly
- Computers & Software for Data Management
- Power Generation & Storage
- Communication Hardware & Software
- Remote Health Monitoring Sensors
- Visual Inspection Hardware & Software
- Cryogenic Fuel Control
- Docking, Berthing Mechanisms
- Lighting Units (Fixed & Moveable)
- Guidance, Navigation & Control
- Storage Mechanisms
- Shielding (Thermal, Debris, Radiation)

Conclusions

In-space assembly and servicing of Mars Space Transfer Vehicles will be required.

The infrastructure required to carry out the assembly and servicing activity is determined by the operational functions.

Within a given range of ETO vehicle sizes the infrastructure requirements are independent of the launch vehicle sizes.

The systems and subsystems defined by this study are the top level requirements for an infrastructure.

The complexity of the operations which must take place in space for assembly and servicing of the Mars STV are independent of launch vehicle size.

The frequency with which the assembly and servicing operations must be carried out is entirely dependent on launch vehicle size.

The functional primitives which have been defined in this study are ideally suited for telerobotic operation.

The 79 day launch centers required for ground based processing of the ETO vehicle is considerably longer than the time required for telerobotic assembly of the STV components.

Recommendations

There are four major recommendations resulting from this study. The first recommendation should carry the highest priority with the other three carrying about the same weight.

1. We must include in-space operational analysis as an integral part of current planning for all future missions. If we fail to consider detail in-space operational analysis from the conceptual mission stage forward we will quickly drive mission costs to unacceptable levels, and jeopardize NASA's commitment to total life cycle quality.

2. We must conduct a more detailed analysis of the interdependencies between in-space operations and ground based processing.

3. We need to carry the operational scenario's presented in this study to a more detailed level, and develop the operational timelines for specific mission scenario's.

4. We should conduct system analysis studies of each proposed Mars STV assembly option (Free Flyer, Saddle, Mini Depot, Platform) with respect to the requirements developed under this study, so that we can better understand their applicability for future use.

In addition numerous lower level recommendations could be generated with respect to developing and refining concepts for In-Space Assembly and Servicing (ISAS) Facility Infrastructures. These recommendations would cover the field from in-depth system/subsystem analysis, through facility concept development, to performing detail life cycle cost analysis of various options. Each of these are essential to developing our ability to live and work in space, and for our journey to other planets.

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In-Space Assembly-Servicing Requirements

Question: Is the Function served by the System/SubSystem, or, is there Any Connectivity between the Function and the System/SubSystem?

Systems/Sub Systems \ Functions	Deploy/Erect Structure	Test/Verify Ass'y/Components	Attach/(dis)Assemble Components	Communicate	Generate/Store Power	Provide Effective Lighting	Inspect Structure/Components	(re)Calibrate Systems/Components	Control Vehicle Attitude	Make Utility Connections	Provide Thermal/Radiation Protection	Manage Cryo Transfer / Connections	Manage Mission Data	Provide Debris Protection	Control Large Space Structures	Receive/Rendezvous/Dock	Checkout Systems/SubSystems	Maneuver Components to Store/Ass'y	Berth/Store Components	Manipulate Structure/Component	Provide for Supportability (#)	# Provide Self Correcting Capability	# Conduct Training	# Store/Transfer Support Systems	# Support Nuclear Systems	# Changeout Components	# Provide/Store Tools/Components	# Capture/Retrieve Loose Objects	# Assist Crew Transfer
Structures																					X								
Truswork(Preintegrated, Space Assembled)	X		X				X				X				X	X			X	X					X		X		
Smart Structures	X	X	X	X			X	X			X		X		X	X	X								X				
Joint Connections	X		X				X			X					X	X			X						X	X	X		
Rails			X													X		X	X						X				
Robotic Systems																					X								
Manipulators (Fixed, Moveable)	X	X	X	X			X	X		X		X				X		X	X	X			X	X	X	X	X	X	
Alignment Sensors	X	X	X	X			X	X		X		X			X	X	X	X	X	X		X			X	X			
Mobile Transporters			X	X				X								X		X		X		X	X		X	X	X	X	
Rail Crawlers			X	X				X					X			X		X		X		X	X		X	X		X	
End Effectors/Tools	X	X	X					X		X		X	X			X		X		X				X	X	X	X	X	
Joining Mechanisms (Bolts, Pins, Latches)	X		X							X		X			X	X			X	X					X	X	X		
Data Management Systems (Computers)																					X								
Artificial Intelligence			X				X	X	X				X		X			X		X		X	X		X				
Large Storage Devices (Gbytes)		X	X	X			X	X	X				X		X		X	X		X		X			X				
Real Time Distributed Processing Devices	X	X	X	X			X	X	X			X	X		X	X		X		X		X			X			X	
Fault Tolerant Systems			X				X	X	X	X		X	X		X		X	X		X		X			X				

Table 1a:

Chief Engineer

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Ver 1 -6/26/92

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Systems/Sub Systems \ Functions	Deploy/Erect Structure	Test/Verify Ass'y/Components	Attach/(dis)Assemble Components	Communicate	Generate/Store Power	Provide Effective Lighting	Inspect Structure/Components	(re)Calibrate Systems/Components	Control Vehicle Attitude	Make Utility Connections	Provide Thermal/Radiation Protection	Manage Cryo Transfer / Connections	Manage Mission Data	Provide Debris Protection	Control Large Space Structures	Receive/Rendezvous/Dock	Checkout Systems/SubSystems	Maneuver Components to Store/Ass'y	Berth/Store Components	Manipulate Structure/Component	Provide for Supportability (#)	# Provide Self Correcting Capability	# Conduct Training	# Store/Transfer Support Systems	# Support Nuclear Systems	# Changeout Components	# Provide/Store Tools/Components	# Capture/Retrieve Loose Objects	# Assist Crew Transfer	-	-	-	-	-
Data Management Software		X	X	X			X	X	X			X	X		X	X	X	X	X	X		X		X	X	X	X	X						
Diagnostics Tools	X	X	X				X	X	X	X	X	X	X		X	X	X			X		X			X									
Automated Checkout Tools	X	X	X				X	X			X	X	X		X	X	X	X				X			X	X								
Teleoperations Intefaces	X	X	X	X			X	X		X		X	X			X		X		X			X	X	X	X	X	X						
Error Recovery Systems								X					X				X			X		X			X									
Task Sequence Systems	X	X	X							X		X	X		X	X	X	X		X		X			X	X	X							
Part Collision/Avoidance Systems	X		X	X									X			X		X		X					X									
Redundancy/Conflict Resolution Systems			X				X		X			X	X		X		X			X		X			X									
Communications Systems (Data, Voice, Video)																					X													
Image Processing Systems	X	X	X	X		X	X	X		X		X	X		X	X	X	X	X	X				X	X	X		X	X					
Cameras	X	X	X	X		X	X			X		X			X	X	X	X	X	X				X	X	X		X	X					
Antenna(s)	X	X	X	X		X	X	X	X	X		X			X	X	X	X	X	X		X			X	X		X	X					
Data Collection/Processing Systems	X	X	X	X		X	X	X	X	X		X	X		X	X	X	X	X	X		X			X	X								
Power Systems																					X													
Radiators					X						X				X							X			X									
Solar Arrays	X	X	X	X	X	X	X	X	X	X		X			X	X	X	X		X		X		X	X	X								
Solar Dynamics	X	X	X	X	X	X	X	X	X	X		X	X			X	X	X		X		X		X	X	X								

687

Table 1b:

Chief Engineer

LaRC/Cockrell:28th Joint Propulsion Conference, July 6-8, '92 (Table1b.MTQ1)

Ver 1 - 6/26/92

LaRC - System Safety, Quality & Reliability Division

In-Space Assembly-Servicing Requirements

Systems/Sub Systems \ Functions	Deploy/Erect Structure	Test/Verify Ass'y/Components	Attach/(dis)Assemble Components	Communicate	Generate/Store Power	Provide Effective Lighting	Inspect Structure/Components	(re)Calibrate Systems/Components	Control Vehicle Attitude	Make Utility Connections	Provide Thermal/Radiation Protection	Manage Cryo Transfer / Connections	Manage Mission Data	Provide Debris Protection	Control Large Space Structures	Receive/Rendezvous/Dock	Checkout Systems/SubSystems	Maneuver Components to Store/Ass'y	Berth/Store Components	Manipulate Structure/Component	Provide for Supportability (#)	# Provide Self Correcting Capability	# Conduct Training	# Store/Transfer Support Systems	# Support Nuclear Systems	# Changeout Components	# Provide/Store Tools/Components	# Capture/Retrieve Loose Objects	# Assist Crew Transfer	-	-	-	-	-
Batteries	X	X	X	X	X	X	X	X	X	X		X	X		X	X	X	X		X		X			X	X								
Power Distribution Networks	X		X	X	X	X	X	X	X	X		X			X	X	X					X		X	X	X		X						
Utility Connections	X		X	X	X	X	X	X	X	X		X				X	X					X		X	X	X								
Cables	X		X	X	X	X	X	X	X	X		X				X	X					X		X	X	X								
Test/Inspection/Validation Systems																					X													
Machine Vision Sensors		X	X				X	X		X			X		X	X	X	X	X	X		X			X	X								
NDE Tools	X	X	X				X	X					X		X		X					X	X		X	X								
Leak/Contamination Sensors		X					X	X		X		X	X				X					X			X	X								
Specialized Inspection Sensors	X	X	X				X	X		X	X	X	X		X		X					X			X	X								
Built In Test Sensors/Equipment	X	X	X				X	X		X	X	X	X		X		X					X			X	X								
Data Collection/Procession Systems	X	X	X				X	X		X	X	X	X		X		X	X	X			X			X	X								
Fuel Management Systems																					X													
Fuel Storage Tanks (GO2, GH2)			X						X			X			X	X									X									
Fuel Transfer Lines			X						X			X			X										X									
Fuel Control Systems (Values,Pumps,etc:)			X					X	X	X		X			X							X	X		X									
Fuel Line Connections/Mechanisms			X					X	X	X		X													X									

Table 1c:

Chief Engineer

In-Space Assembly-Servicing Requirements

Systems/Sub Systems \ Functions	Deploy/Erect Structure	Test/Verify Ass'y/Components	Attach/(dis)Assemble Components	Communicate	Generate/Store Power	Provide Effective Lighting	Inspect Structure/Components	(re)Calibrate Systems/Components	Control Station Attitude	Make Utility Connections	Provide Thermal/Radiation Protection	Manage Cryo Transfer / Connections	Manage Mission Data	Provide Debris Protection	Control Large Space Structures	Receive/Rendezvous/Dock	Checkout Systems/SubSystems	Maneuver Components to Store/Ass'y	Berth/Store Components	Manipulate Structure/Component	Provide for Supportability (#)	# Provide Self Correcting Capability	# Conduct Training	# Store/Transfer Support Systems	# Support Nuclear Systems	# Changeout Components	# Provide/Store Tools/Components	# Capture/Retrieve Loose Objects	# Assist Crew Transfer	-	-	-	-	-
Life Support Systems																					X													
Habitats						X		X			X		X	X		X													X					
Closed Loop ECLSS								X					X									X							X					
Manned Systems								X					X		X		X					X	X						X					
EVA/IVA Systems (Suits, Airlocks)		X				X		X					X		X	X	X			X		X	X	X					X					
Lighting Systems	X	X	X		X	X	X										X				X			X		X			X					
Docking Adapters			X												X	X			X		X			X	X	X		X	X					
Latching Mechanisms	X		X					X		X		X			X	X			X		X			X	X	X	X	X	X					
Thruster Pods								X	X						X	X		X			X	X							X					
Attitude Control Systems							X	X	X				X		X	X		X			X	X							X					
Control Moment Gyros							X	X	X				X		X	X		X			X	X							X					
Storage Enclosures											X			X	X				X		X			X		X	X	X						
Shielding											X			X	X						X		X		X									
Safety Contingency Systems		X		X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	X	X	X	X	X			X					

Table 1d

Chief Engineer

LaRC/Cockrell:28th Joint Propulsion Conference, July 6-8, '92 (Table1d,MTQ1)

Ver 1 - 6/26/92