Report of

Space Transportation Systems Life Cycle Cost Assessment and Control

Produced by

THE SPACE PROPULSION SYNERGY TEAM'S (SPST) FUNCTIONAL REQUIREMENTS SUB-TEAM

For the:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION HEADQUARTERS OFFICE

Director Strategic Investments

Appendix VII insertion to reduce file size
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Executive Summary

Recommendations. The SPST is recommending NASA adopt the proven methods of controlling weight and performance and applying them to controlling cost. The SPST recommends that the Program Analysis and Evaluation Office endorse the approach and procedures to life cycle costs assessment control described in this report. Further the SPST recommends that these new approaches and procedures be implemented within the current planning of the Space Exploration Vision Missions. We emphasize these recommendations, because, the Space Exploration Vision must not only be "affordable" but "sustainable". This requires close control of "life cycle costs" within established budgets.

Objective of this report. The ultimate objective of this report is to assure that the planning and implementation of the transportation systems required by the Space Exploration Program takes maximum advantage of the "lessons learned" from the major space programs of the past decades. The focus of the report is on what has been learned about the assessment and improving control of Life Cycle Costs (LCC) from these major space programs. The major "lesson learned" from these studies is that much improved, innovative processes must be developed and rigorously applied to effectively control life cycle cost.

The only major objective that was controlled in these past programs by a structured Engineering Management process was performance closure by managing flight systems weight. Objectives were set for Life Cycle Cost (LCC) for the Shuttle, but no Engineering Management processes were exercised to provide control (only the DDT&E cost was tracked).

For example, the Saturn/Apollo lunar exploration program was terminated early because the recurring transportation cost was not sustainable while supporting the exploration efforts. The reusable Shuttle transportation system was developed to replace the Saturn launch vehicle in an effort to greatly reduce the recurring cost of transportation. Therefore, the lesson learned was that the space transportation system LCC must be controlled to provide a sustainable space exploration program. The major part of the space transportation LCC is the recurring or operational phase cost.

To accomplish this critical objective, this report provides the results of a selected number of studies and analyses that have been conducted by the Space Propulsion Synergy Team (SPST). These directly address the "lessons learned" from previous transportation systems, as well as solutions for improvement and a proposed option to control LCC by controlling the major operational technical functions that greatly influence LCC through the use of requirements and Engineering Management control processes.

Lessons Learned from SPST Studies. The Space Propulsion Synergy Team is quite unique in its organization, membership and capability of addressing this objective. It was chartered by NASA over a decade ago and has a diversified membership of retired and active senior engineers, managers and scientist from industry, government and academia who have a wealth of "hands on" hardware and management experience. The SPST was and continues to be dedicated to the development and operation, of safe, dependable, affordable and sustainable space transportation systems. This is generally believed to be the key element in the NASA's ability to meet the goals of the recently announced Space Exploration Program and commercializing space business.

Since its beginning, the SPST has focused on addressing and developing "out of the box" innovative engineering systems integration and program management approaches and processes that are "key" to meeting the challenging space transportation systems requirements inherent in the current Space Exploration Initiative. A major source of knowledge utilized by the SPST was a study conducted of the "shortfalls" of current space transportation systems (Space Shuttle) to determine and document the shortfalls that developed between initial requirements/objectives and the actual results achieved. The results of this study are included in this report. A major "lesson learned" from these activities is the importance of first clearly defining, flowing down, and controlling the "systems requirements" and maintaining control throughout the R&D Program. The SPST has emphasized the need to clearly define the "requirements" up front: that is the "what's" required of the desired space transportation system. These requirements must cover all major objectives, not only "performance", as was the case in the past, but also in terms of the "functional (operational) requirements" required in the system to achieve sustainable Life Cycle Cost, safety and the country's support. To sum up this lesson learned, we must change the way we do business to avoid "doing what we always do and achieving what we always got". Therefore, we must change our Engineering Management processes to include a structured process to control those major operational functions that are major cost influences to provide the LCC controls required for a sustainable Space Exploration Program.

Recently the SPST developed a new approach for formulating "requirements" that will provide full accountability of all functions required to perform the planned space missions. The approach as described in this report was to develop a top-level functional systems breakdown structure, (Functional SBS) with modular sub sets, that may be utilized as a basis for defining the desired "functional requirements" in any space system. This process is intended to serve as a guide in development of the work breakdown structure (WBS), provide visibility of those technologies that need to be enabled to cover a required function, and help identify the personnel skills required to develop and operate the space transportation system for this very large and challenging National effort. This Functional SBS covers all transportation elements on earth, the moon and mars including any orbiting operational space nodes if deemed necessary.

Another study performed by the SPST was a "bottom-up" analysis which addressed the question of why past programs weren't achieving the desired functional criteria: "what has impeded or prevented the application of good systems engineering and management's successful implementation of the approaches/processes addressed in this report?" Results are very interesting and deserving of more in depth attention. For example, it was found that there are several reasons for the impediments: lack of overall integration (stove-piping or optimizing at the single function level), inappropriate starting technology level, the lack of sufficient Engineering Management processes, and that many of the systems engineering requirements (needs), were "boring" not stimulating (not sexy). This indicates that major improvements in discipline must be rigorously imposed on the system engineering and design processes by the program managers.

This represents only a small example of the products that would be helpful to the NASA's space challenge and the SPST is available to use its capabilities and resources to address the issues hi-lighted in this report.

1.0 Introduction

In June, 2005, SPST presented a proposal to NASA's office of Director Strategic Investment personnel that was made up of 3 tasks. One of these tasks was addressing space transportation systems LCC assessment and control. It was stated that NASA had always been interested in achieving LCC control, but the question was "HOW". The SPST has responded to this challenge and this report is presenting a proposed option to greatly improving on the achievement of controlling the LCC.

Civil and military applications of Space Transportation have been pursued for 50 years and there have been and there is now an even greater need for safe dependable affordable and sustainable space transportation systems. Fully expendable and partially reusable space transportation systems have been developed and put in operation. Access to space is technically achievable, but presently very expensive and will remain so until there is a breakthrough in the way we do business. The approach to providing the propulsion systems functions has a major influence in achieving the affordable/sustainable objectives and again will require a breakthrough in the way we have been doing systems engineering and management.

A critical need for improved communications between the user and the developer led to NASA's Code R and Code M chartering the Space Propulsion Synergy Team in 1991. This SPST's first task was to use its member's diversified expertise toward developing new "Engineering Management Decision Making Tools": specifically developing innovative engineering processes in the architectural design, development, and operation of space transportation systems to satisfy the challenging requirements of both the transportation operators and the payload customers. The SPST established a dialogue between the personnel involved in all phases of the technology, design, development, and operation of a space transportation system.

The major theme of the SPST processes is an emphasis on "developing" the Space Transportation System "Requirements" first (up front) that address and respond to the key objectives desired and these requirements must include both the usual system flight performance and the system functional requirements as well as the total infrastructure on Earth, In-Space and on the Moon and/or Mars surface to determine Life Cycle Costs.

This report describes the development of these specific innovative engineering and management approaches and processes that were developed and in use today. The major change the SPST is proposing is to improve the control of Life Cycle Cost using major cost influencing Program Metrics rather than just controlling the vehicle flight performance and/or mass.

The SPST has reviewed the following Shuttle documents to determine possible modifications needed in the ESMD documents for tracking and controlling Life Cycle Cost:

- Level 1 NSTS Requirements
- Level 2 NSTS Requirements

- Level 3 NSTS Requirements

This review has helped the SPST develop and document the logic and rationale on how to provide LCC controls/requirements in the ESMD documents.

The basic approach by SPST to the task of providing "Space Transportation Systems Life Cycle Cost Assessment and Improving Control" is to adapt the use/approach of the management process for weight control system/approach that NASA used on the Space Shuttle Program to control Life Cycle Cost for the Space Exploration Program. This includes technology, advanced development, DDT&E, Manufacture, Operational, and Recycle/Disposal plus all the infrastructure cost on Earth, Moon and Mars. This will require a major cultural adjustment to the way the US Government in general and NASA/Aerospace support industry specifically do business, since Life Cycle Cost—womb to tomb cost, has not been included in the traditional Program focus (we have never focused on trying to develop and control a sustainable space exploration program). Commercial enterprises all budget and control their projects/programs to Life Cycle Cost; otherwise they fail and go out of business.

The SPST proposes to address the global problem of budgeting and controlling Life Cycle Costs by assuring all requirements are in place from Level 0 to the unique element requirements level that address all the major objectives (performance, affordability, safety and sustainability) of the Exploration Program's transportation system. Our recommended option to achieve these results is the use of structured engineering management processes to budget and control those functions that are the primary LCC drivers of the space transportation system.

2.0 The Proposed Approach

The objective was to define the major operational cost drivers (support infrastructure, labor, and material) that must be controlled to allow the management of recurring side of Life Cycle Cost. An example of the "Systems Engineering Management Process" needed to provide the necessary LCC controls will be developed to the level of use within the Exploration Systems Mission Directorate requirements documentation system. The following products of previous SPST Sub Team Activities will be used in development of the required new "Systems Engineering Management Processes" and they will be included in the deliverables, which will be made available upon task completion.

- Generic Functional Systems Breakdown Structure (Generic Functional SBS) defining all requirements that need to be addressed in the vision for Space Exploration Initiative to cover the total space transportation system
- Assessment of System Impediments and Corrective action required based on "Bottom Up" Analysis"
- Managing Life Cycle Costs Based on "Lessons Learned" (Current Space Transportation Systems Shortfalls resource material)

The approach to defining and controlling life cycle costs consisted of two major parts. One part concentrated on "lessons learned" from the design and operations of previous Space transportation systems including the shortfalls in the performance and operation of the Space Shuttle. The other part of this SPST activity has focused on developing and applying innovative approaches to system engineering management process needed to provide LCC control (a first step).

3.0 Background (SPST Supporting Analysis and Studies)

3.1 Space Shuttle

Although the Space Shuttle is a highly successful program, the first of its kind, and has produced cutting edge technology, it is not an example of a low operating cost, short turnaround architecture. By looking at its history, what were its major objectives and goals and what was actually achieved, the need to focus on specific areas was made visible and a number of "lessons learned" were derived.

3.1.1 Space Shuttle Shortfalls

The "US Space Shuttle Shortfalls" provided the rationale for **Space Transportation Systems Life Cycle Cost Assessment and Improving Control** to be completed early so the Life Cycle Systems Engineering and Integration (SE&I) Life Cycle Cost (LCC) disciplines can be applied in the initial definition of the space exploration program establishing LCC as the major and overriding metric for all hardware and software implementation programs.

The Space Shuttle is not adequate to accomplish the spectrum of NASA-missions goals (not sustainable) because current space activities are constrained by the following:

- Operational flexibility and responsiveness – flight rate has not achieved concept goals.
- Operated by RDT&E personnel—the developer (instead of "commercial-style" operations personnel) with resultant high operations cost – there is no reward incentive, or system, to support "order-of-magnitude" cost cutting.
- Limited in-space maneuver capability – science and logistic mission scopes are not all-inclusive of agency vision.
- Concern for safety and reliability is constrained to the system architecture – what you see is what you get.
- Significant constraints on payload mass and volume – greater "Operability" (flight rate) is needed to reduce historical LCC ($/PL lb to orbit/year) and provide much larger annual mass-throw capability; i.e., the learning curve.

The SPST Functional Requirements Subteam prepared a table which shows the current capabilities of the Space Shuttle and the Critical Shortfalls relative to the initial space shuttle requirements. This table can be found in the Appendix I

3.1.2 Space Shuttle Level 1 Program Requirements Document

To stand any chance of controlling LCC the program must place firm requirements on the Programmatic, Technical, and Operational requirements of the program; flow them down to each stage/element involved; and then apply the requirements through the design process. Therefore, presented here are excerpts from the Shuttle Program requirements documentation demonstrating how they established and controlled the performance objective by controlling the weight of the integrated flight system, its major elements (Orbiter, ET, SRB, SSME, etc) down to each of the sub-system (wet and dry weights) involved. It's this structured engineering management process that's being recommended to also establish and control these eighteen operational performance metrics (See section 4.0) for the NASA's exploration program. Space Shuttle Program documentation excerpts of interest can be found in the Appendix II

3.2 A Generic Functional Systems Breakdown Structure (SBS) for Space Transportation Architectures

A Functional SBS is a method that will provide a successful framework for defining and specifying the requirements and can also be used for determining the general support infrastructure needs. It also can serve as a guide for insuring LCC assessments have full accountability of all functions required.

A generic functional SBS provides a universal hierarchy of required space transportation operational functions, which include ground and space operations as well as infrastructure. The matrix provides a structured, indentured breakdown of Systems' Functional System Requirements for the use in design definition and accountability for all functions; i.e., a giant check list to be sure that no functions are omitted especially in the early architectural design phases.

The Functional SBS furnishes inputs for analysis of any concept and provides a systematic source for determining and documenting the requirements and the "Life Cycle Costs" necessary to achieve the Program/Project goals and objectives. When used correctly, the Functional SBS furnishes a framework for defining requirements, which will preclude over or under specifying these requirements.

This Functional SBS provides inputs for analysis of concepts and provides a source for determining and documenting requirements necessary to achieve full accountability of Top Level Goals. This Functional SBS will also serve as a guide to assure that the required skills are available to support the program's needs.

3.3 SPST Support of Spaceliner 100 Technologies Planning

Besides examinations of the Shuttle and ground operations, the SPST has also been involved with NASA in the identification of specific technologies needed to achieve safer and lower cost access to space. One example of a major effort occurred in 1999-2000.

At a meeting of the Space Propulsion Synergy Team (SPST), in October 1999, Mr. Garry Lyles, Manager of the MSFC Advanced Space Transportation Office, formally requested the support of the SPST in the development of a Spaceliner 100 Technology Plan. In response to NASA's request, the SPST team agreed to provide technical and programmatic support to NASA in formulating a "Spaceliner 100 Technology Program".

This was a significant effort involving both SPST and non-SPST personnel and a multi-day workshop at MSFC. It produced prioritized technologies for GRC and MSFC use in their internal planning.

The approach used in this effort to determine the needed technologies was a "top-down" approach: the goals were identified, the potential systems were defined, and the resulting needs led to technologies to fill the needs.

The support was carried out by three teams that produced the inputs necessary to hold a technologies assessment and prioritization workshop at MSFC, and by conducting that workshop. The product was sets of prioritized technologies in three areas for MSFC/ASTP's use.

The Functional Requirements Team expanded, and further defined, the basic functional requirements of an RLV/Generation 3 transportation service. This expansion included transportation service capabilities and customers. In addition they defined other major attributes, including responsiveness, dependability, and environmental compatibility as “functional requirements”.

This team also provided a vital input to the Assessment and Prioritization Workshop Team. They “identified and weighted” the measurable technical design criteria and programmatic assessment factors.

In parallel, the Transportation Architectures Team was identifying the transportation system “architectures” that were considered to have the potential of meeting these requirements.

The Technologies Identification Team used the output of both of these teams in identifying and defining the candidate propulsion system technologies. Once this team had identified and categorized the candidate technologies they were responsible for the development of “white papers”, quad charts, briefings, and criteria tables on each.

The last step was the actual assessment and prioritization. This was conducted in a “hands-on workshop” on April 5 – 7, 2000 at MSFC by the Technologies Assessment and Prioritization Workshop Team.

The work was carried out from October 1999 through April 2000. An example of this work can be found in the Appendix III.

3.4 SPST Integrated Technology Subteam (Bottom-up)

The efforts described in Section 3.3 represent a "top-down" approach to identifying technologies needed to achieve the goals of safer and lower cost access to space. The goals are identified, the potential systems are defined, and the resulting needs lead to technologies to fill these needs.

In 2002 and 2003 an attempt was made to attack the problem from another direction to examine if the resulting technologies identified would be different. This was described as a "bottom-up" effort where first the impediments to implementing technology solutions were identified and then solutions to the impediments proposed. This was followed by identification of systemic technology needs.

3.4.1 Impediments to “Bottom-Up Integration

There are numerous impediments to why traditional space transportation existing and concept systems are not achieving the desired operational cost influencing characteristics resulting in affordable, safe, and sustainable approaches. These impediments need to be understood as to why technology solutions are not focused on the desired design criteria and are not implemented. These impediments need to also be understood in context of the following technology concept solutions:

- Testing and verification of existing paradigms
- Heritage and implementation cost
- Experience base/systems engineering to evaluate does not exist
- It is not fun
- A structured requirements, traceability and accountability process for key operational performance criteria does not exist
  - Operability—access, inspection, reduction of operations activities, e.g., not optimized at the total system level (presently optimized at the lowest sub-system level)
  - Reliability—functional redundancy, elimination of failure modes
  - Maintainability—hardware dependability meets the true operational environment expected without unreasonable depot maintenance frequencies
- Not evaluated by const/benefit or maximum leverage
  - Detailed quantitative analysis required
- Concepts correlation exercise showed that all proposed technologies are strongly cross cutting
  - Required by all concepts to achieve objectives
  - Impediments to achieving majority of solutions seem manageable

Results of Bottom-Up Team Prioritization can be found in the Appendix IV.

4.0 Space Transportation Systems Life Cycle Cost Assessment and Improving Control

4.1 Proposed Operability Design Requirements Technical Performance Metrics (TPMs)

The proposed Exploration Vision must be "sustainable" (i.e., it must be within budget and within yearly budget caps both during procurement and throughout its long operating life). For this to be achievable, operability must be designed into the architectures and elements from the very beginning. Indeed, NASA is attempting to implement this as shown by **NASA NPR: 7120.5C (This document is a "Must Read")** dated February XX, 2005. NASA Program and Project Management Processes and Requirements, **Paragraph 6.2.3 Systems Engineering Requirements:** The Project Manager and project team shall:

> (a.) With the Program Manager, customers, and stakeholders, define a validated set of Level 1 requirements and success criteria for the project in Phase A.
> (b.) Develop operations scenarios and concepts, mission profiles, and mission operational modes for the purpose of fostering a better understanding of operational requirements, including LCC drivers for logistics and maintenance.

To further this effort the Space Propulsion Synergy Team has developed, over a number of years and a number of separate tasks, a series of Technical Performance Metrics (TPMs) that would help assure sustainable operational space transportation system architecture. The following section lists and defines these TPMs.

4.2 How to Improve the Control of Life Cycle Cost (LCC)

The following are recommended "Design for Operability" requirements TPMs. The purpose of these "requirements" is to guide and control the development of the overall and element architectural concepts and the designs of vehicle components, subsystems and systems in order to minimize and control LCC by focusing on operations and maintenance costs drivers. These needs are a response to the shortfalls analysis performed on the Shuttle program and reflect the major lesson learned. The process used to select these TPMs has been developed over the years by the SPST by using the Total Quality Management (TQM) tool Quality Functional Deployment (QFD). These results were supplemented by the Shuttle Shortfall Analysis study. A sample of this process is provided for your insight in Appendix VII

A listing of those focus-area measurable criteria that require an Engineering Management structured process established within the requirements documentation are as follows:

1. Total number of separate identified vehicle propulsion systems (lack of discipline functional integration). This also applies to # of separate stages: **Metric Nominal Target Value:** 2, e.g., Integrate MPS, OMS, & TVC and integrate RCS, FC power & Thermal Management, i.e., low pressure storage vs. supper critical storage
   Shuttle Reference Value: Many systems in MPS, OMS, RCS, TVC, Thermal Management Systems and Life Support Systems (12 of these in orbiter)
   Discussion: Traditional practice of designing separate stand-a-lone propulsion systems for ascent (MPS), reaction control (RCS), de-orbit and space maneuvering (OMS), and thrust vector control (TVC) could be provided by a single integrated system. This would result in a reduction in tanks, pressurization, and interface systems which will result in a very large reduction in flight hardware and ground support infrastructure. Traditional lack of integration adds un-necessary hardware that adds weight, many ground servicing interfaces at several ground stations and a very large logistics support infrastructure for replacement parts for both the flight

and ground systems. It also reduces the reliability while decreasing the safety of the vehicle resulting in a very large added maintenance burden to the operations. These servicing interfaces may also become applicable in-space or at ground-node sites on the moon or mars. These separate flight systems also require additional turnaround time for servicing. Operations that add turnaround time drive the need for fleet support to meet the mission needs of the operation which require both additional flight elements and dedicated ground support facilities and equipment. This places a very large increase on the LCC of the program. This impact will be multiplied when considering "ground nodes" like the moon, mars, and lunar, mars, & earth orbit stations.

The number of separate stages: This impact will be exasperated and multiplied when considering the support infrastructure from all the added separate systems, plus stage interface systems, and their logistics supply chain. This places a very large increase on the LCC of the program.

2. Total number of flight tanks in the architecture: **Metric Nominal Target Value:** 12, LP fuel, LP Lox, 2 gas pressurant tanks, 2 H2O tanks, 2 GO2 tanks, 2 supper critical storage fuel & 2 supper critical Lox tanks

   Shuttle Reference Value: In excess of 95

   Discussion: Every tank on the vehicle will require pressurization and down-stream feed distribution systems. This adds un-necessary hardware and flight weight, a very large logistics support infrastructure for replacement parts and a large ground infrastructure for storage, distribution, and transfer operations to the vehicle interfaces for servicing. It also requires logistics support for procurement, quality control verification, special cleaning processes etc. for replacement hardware. These impacts add very large cost (LCC) to the program and decrease the safety of the operation

3. Number of safety driven functional requirements to maintain safe control of systems during flight and ground operations: **Metric Nominal Target Value:** 7, 2 He bubbling of cryo for thermal conditioning, Lox turbopump seal purge, 2 cryo umbilical purges, 2 engine shutdown purges

   Shuttle Reference Value: In excess of 70

   Discussion: Critical functional systems like the Lox anti-geysering He purge, the Lox turbopump seal He purge, pogo suppression, hazardous gas detection systems, and compartment purges are examples of these functions. These functions are required to prevent loss of vehicle both on the ground and in flight. Reducing these functions by selecting an architecture that deletes its need will increase the safety and reduce hardware (weight savings) required providing a very large life cycle cost savings. These functions all increase the turnaround time and manpower to perform the O&M of these added systems as well as an increased flight hardware logistics support system. Operations that add turnaround time drive the need for fleet support to meet the mission needs of the operation which require both additional flight elements and dedicated ground support facilities and equipment. These impacts add large cost (LCC) to the program and decrease the safety of the operation. This impact will be multiplied when considering "ground nodes" like the moon, mars, and lunar, mars, & earth orbit stations.

4. Number of maintenance actions unplanned between missions: **Metric Nominal Target Value:** ≤ 1, Balancing the R, M & S requirements should drive this result
   Shuttle Reference Value: ~ 800
   Discussion: The total number of active components either drives the needed component reliability level (increasing the DDT&E cost) or the use of redundancy needed to reach the desired system reliability to enable overall system safety. This traditional practice of using multiple string components and systems places a very large maintenance burden on the operations which drives the unplanned work content and time during turnaround on the ground, on the moon or mars and at ground nodes like lunar or earth orbit stations. This practice destroys the system integrity during turnaround and the need to recertify the system for every flight. Operations that add turnaround time drive the need for fleet support to meet the mission needs of the operation which require both additional flight elements and dedicated ground support facilities and equipment. These impacts add large cost (LCC) to the program and decrease the safety of the operation.

5. Number of maintenance actions planned between missions: **Metric Nominal Target Value:** 00, Requirement for IVHM/Full automation should produce this result
   Shuttle Reference Value: ~ 2200
   Discussion: Limited life or expendable hardware along with required inspections or checkouts require access equipment, disrupt system integrity, and lengthen the turnaround time. The requirement for these functions will drive the need for every flight re-certification which is very costly. Operations that add turnaround time drive the need for fleet support to meet the mission needs of the operation which require both additional flight elements and dedicated ground support facilities and equipment. These impacts add large cost (LCC) to the program and decrease the safety of the operation. This impact will be multiplied when considering "ground nodes" like the moon, mars, and lunar, mars, and earth orbit stations.

6. Total number of traditional ground interface functions required: **Metric Nominal Target Value:** 4, Fuel, Ox, electrical & HP gas
   Shuttle Reference Value: Hundreds
   Discussion: Every additional function adds ground support systems (GSE), facilities, direct labor and considerable in-direct infrastructure and support. These added functions increase LCC and decrease safety. Some examples of these functions are mating operations, inspections, adding temporary environmental protection, planned maintenance, un-planned maintenance and replacing expendable items. These additional ground interface functions require added turnaround time for servicing. Operations that add turnaround time drive the need for fleet support to meet the mission needs of the operation which require both additional flight elements and dedicated ground support facilities and equipment. This places a very large increase on the LCC of the program. . This impact will be

multiplied when considering
“ground nodes” like the moon, mars, and lunar, mars, & earth orbit stations.

7. Percent (%) of all systems automated: **Metric Nominal Target Value:** 100% - IVHM, This is doable if effort is made to make traditional mechanical hardware smart
   Shuttle Reference Value: (Inspections and checkout mostly manual)
   Discussion: Many manual intrusive inspections and functional verifications are required before every launch. Also the many redundant subsystems and components that perform critical functions that could cause loss of life or vehicle must be verified before flight in order to establish there really are redundant capabilities. These manual functions require much labor and schedule time to perform. To affectively utilize the redundant hardware there needs to be an automated management capability to avoid a large ground monitoring capability needed to timely respond to failed critical hardware or subsystems. These traditional manual impacts add large cost (LCC) to the program and decrease the safety of the operation.

8. Number of different fluids required: **Metric Nominal Target Value:** 4, Fuel, Ox, HP gas, & water
   Shuttle Reference Value: 24 every flight
   Discussion: Each additional fluid requires a costly ground infrastructure for storage, distribution, and transfer operations to the vehicle interfaces. It also requires logistics support for procurement, quality control verification, special cleaning processes etc. Each fluid dictates at least one additional vehicle interface that must be serviced. Some of these fluids being toxic require a medical support operation to maintain reference information on each of the personnel being subjected to the possible exposure along with special training. Several of these toxic fluids also require the personnel to wear self contained garments which also require a support group to maintain the garments. These impacts add very large cost (LCC) to the program and decrease the safety of the operation. . This impact will be exasperated and multiplied when considering servicing at “ground nodes” like the moon, mars, and lunar, mars, & earth orbit stations.

9. Total number of vehicle element to element support systems (Major element interfaces such as Orbiter to SSME or ET): **Metric Nominal Target Value:** 12, Fuel feedline, Ox feedline, Fuel repress line, Ox repress line, 2 electrical power, 2 data, 3 structural attachments (gimble & 2 TVC)
   Shuttle Reference Value: Example is the SSME with 26 support systems from the Orbiter for each SSME
   Discussion: This adds un-necessary hardware that increases vehicle weight, a very large logistics support infrastructure for replacement parts and reduces the reliability while decreasing the safety of the vehicle and resulting in a very large added maintenance burden to the operations. This places a very large increase on the LCC of the program. Example where this practice on the Shuttle is the SSME requiring both hydraulics and pneumatics for valve control and both sub-systems use electromechanical components to effect the controls. The basic valve could be

controlled by an electromechanical device eliminating the other support systems in their entirety.

10. Number of flight vehicle servicing interfaces: **Metric Nominal Target Value:** 14, LH2, Lox, HP He, 2 ele power, Fuel cell reactant LH2 & Lox, H2O, 2 data, Cabin air, Waste removal, HP O2 & HP N2
    Shuttle Reference Value: ~102
    Discussion: Each additional interface requires a large ground infrastructure for storage, distribution, and transfer operations to the vehicle interfaces. This impact is repeated for every facility the vehicle occupies during the ground turnaround operation. It also requires logistics support for procurement, quality control verification, special cleaning processes etc. These interface systems require time and personnel to provide this connection and disconnection for each facility being used by the vehicle element. This adds considerable time and labor to the turnaround flow decreasing the vehicle's operational effectiveness. Operations that add turnaround time drive the need for fleet support to meet the mission needs of the operation which require both additional flight elements and dedicated ground support facilities and equipment. These impacts add very large cost (LCC) to the program and decrease the safety of the operation. This impact will be exasperated and multiplied when considering servicing at "ground nodes" like the moon, mars, and lunar, mars, & earth orbit stations.

11. Number of confined/closed compartments: **Metric Nominal Target Value:** 1, Crew Cabin
    Shuttle Reference Value: 13 or more
    Discussion: Closed compartments that provide possible entrapment of combustible gases/fluids require addition of purge systems, hazardous gas detection systems, and corrective actions when required to provide safe control of system. These compartments require an inert purge during hazardous operations, but require a conversion to a life supportable environment before personnel can enter to perform corrective action when required. All the above functions drive the need for added ground infrastructure/systems resulting in a large increase in cost and added turnaround time. Confined spaces limit access for planned operations and unplanned maintenance adding to the turnaround time and decrease the safety of the operations. Added turnaround time drives the need for added vehicles and ground facilities/GSE adding even more cost. Operations that add turnaround time drive the need for fleet support to meet the mission needs of the operation which require both additional flight elements and dedicated ground support facilities and equipment. This impact will be exasperated and multiplied when considering servicing at "ground nodes" like the moon, mars, and lunar, mars, & earth orbit stations.

12. Number of commodities used that require medical support operations and routine training: **Metric Nominal Target Value:** 0 Toxics & 3 Special Training, Cryogenics, HP Gases, & Solid Propellants
    Shuttle Reference Value: 3 major & 3 minor toxic fluids

Discussion: The use of toxic substances and fluids require the operating personnel to provide current reference data on their health and body functions so that in the event of exposure the medical personnel can provide the proper corrective action deemed necessary if accidentally exposed. Also working with cryogenics, high pressure gases, toxics, ordnance and confined environments require special training of operations personnel. This added support function adds life cycle cost to the ground operation. This impact will be exasperated and multiplied when considering servicing at "ground nodes" like the moon, mars, and lunar, mars, & earth orbit stations as it will require handling and transport of these commodities to these other locations.

13. Number of safety driven limited access control operations: **Metric Nominal Target Value:** 9, Pressurizing 3 fluids HP gas tanks to flight level, Servicing 2 super critical cryo fluids, Servicing 2 low pressure cryo fluids, & 2 heavy lift operations
    Shuttle Reference Value: In excess of 266 functions
    Discussion: This addresses confined compartments, hazardous operations like lifting large loads, working with ordnance/explosives, toxic substances/fluids, lasers or microwave energy devices, high voltage power, high pressure gases, cryogenics and x-rays. Limited access is required to limit the exposure to only those directly involved in that operation; therefore limiting the number of personnel required to take corrective action in the event of an unplanned event. Workings with these hazardous operations require special training for personnel involved. These limited access operations have a very large impact on the turnaround time and support operations functions. Operations that add turnaround time drive the need for fleet support to meet the mission needs of the operation which require both additional flight elements and dedicated ground support facilities and equipment. These impacts add large cost (LCC) to the program and decrease the safety of the operation.

14. Number of safing operations at landing: **Metric Nominal Target Value:** 1, Vent high pressure gas tanks to 50% level
    Shuttle Reference Value: 6
    Discussion: These added safing operations subject ground personnel to hazardous conditions, and adds considerable turnaround time. This safing operation requires dedicated ground support equipment for access and servicing, which adds considerable time and labor to perform the required maintenance and provide logistic support. Operations that add turnaround time drive the need for fleet support to meet the mission needs of the operation which require both additional flight elements and dedicated ground support facilities and equipment. These impacts add large cost (LCC) to the program and decrease the safety of the operation. To provide both ground and water landing/recovery compounds this impact.

15. Number of mechanical element mating operations (element to element & element to ground): **Metric Nominal Target Value:** Example 9 for each rocket engine, 2 low

pressure feed lines, 2 HP repress lines, 2 electrical power/data connectors, 2 TVC attachments, gimble block support

Shuttle Reference Value: Example there are 24 component mating between the one SSME and the Orbiter (A total of 72 total SSME mechanical connections to the Orbiter)

Discussion: Many mechanical mating operations requires lifting of large loads subjecting ground personnel to hazardous conditions, and adds considerable turnaround time. This mating operation generally requires a dedicated ground station for integration which adds considerable facility and ground support systems that again require maintenance and logistic support. Element to element mating functions require labor for connection and functional verification. Operations that add turnaround time drive the need for fleet support to meet the mission needs of the operation which require both additional flight elements and dedicated ground support facilities and equipment. These impacts add large cost (LCC) to the program and decrease the safety of the operation.

16. Number of separate electrical supply interfaces: **Metric Nominal Target Value:** Example 2 for each rocket engine to vehicle, 2 electrical power/data connectors

    Shuttle Reference Value: Example: there are 12 electrical components mating needed for each SSME to the Orbiter (A total of 36 total SSME electrical connections to the Orbiter)

    Discussion: Each additional interface requires a large ground infrastructure for storage, distribution, and transfer operations to the vehicle interfaces. This impact is repeated for every facility the vehicle occupies during the ground turnaround operation. It also requires logistics support for procurement, quality control verification processes, etc. Element to element mating functions require labor for connection and functional verification. These impacts add large cost (LCC) to the program and decrease the safety of the operation. Distribution of unique electrical needs can be provided more efficiently on board (like a TV set) without the added impact of driving this function to the ground side of the interface. This total system (flight & ground) improvement should even result in decreased vehicle weight.

17. Number of intrusive data gathering devices: **Metric Nominal Target Value:** 00

    Shuttle Reference Value: Example is there are 45 intrusive sensors on each SSME

    Discussion: Intrusive instrumentation requires those systems being monitored to be drained and conditioned prior to replacement along with re-establishment of the supported system's integrity verification when replacement has been accomplished. This replacement operation is very costly in time and labor for fluid systems with emphasis on toxic and cryogenic systems. Even accessibility is a form of intrusiveness and can cause an operation of less than one hour to become four or five days (example: SSME engine controller replacement from an on-pad abort). These operations always drive additional turnaround time. Operations that add turnaround time drive the need for fleet support to meet the mission needs of the operation which require both additional flight elements and dedicated ground support facilities and equipment. These impacts add large cost (LCC) to the program and decrease the safety of the operation.

18. Number of Criticality – 1 (Crit-1) system and failure analysis modes: **Metric Nominal Target Value:** TBD
    Shuttle Reference Value: Example is that there are 550 Crit 1 & 1R failure modes on each SSME
    Discussion: These Crit-1 failure modes require functional verification between flights and their backup redundant modes verified as well because of their criticality to the vehicle operation. More Crit-1 failure modes cause higher probability of failure (less safe operation and higher probability of loss of vehicle). The verification tasks, inspection & checkout extend turnaround time and increase labor resulting in increased cost. Operations that add turnaround time drive the need for fleet support to meet the mission needs of the operation which require both additional flight elements and dedicated ground support facilities and equipment. These impacts add large cost (LCC) to the program and decrease the safety of the operation.
    Integrated system fail-safe assurance: All designs from the total integrated system, sub-systems, down to the individual component should exhibit fail-safe assurance passively (inherent fail-safe feature within the design).

Reference case 1 and 2 of data for the Shuttle in enclosed as Appendix V and VI.

5.0 Summary

The shuttle shortfalls assessment provided insight into the major areas that needed improvement as well as to the kind of operational criteria that needed to be addressed. This assessment along with the operational areas identified by the "bottom-up" task that provided a high potential for cost reduction allowed the formulation of the proposed operability design requirements technical performance metrics (TPMs). The "bottom-up task also provided the insight that a structured engineering management process would be required to budget and control the TPMs throughout the entire concept to DDT&E completion phases of any future program for LCC controls needed to attain a sustainable NASA exploration program.

The objective of this report is to assure that the planning and implementation of the transportation systems required by the Space Exploration Program takes maximum advantage of the "lessons learned" from the major space programs of the past decades. The focus of this report was on what has been learned about the assessment and improving control of Life Cycle Costs (LCC) from major space programs. The major "lesson learned" from these studies is that much improved, innovative processes must be developed and rigorously applied to effectively control life cycle cost.

The only major objective that was controlled with the use of a structured Engineering Management process was performance closure by managing all flight systems weight. Objectives were set for Life Cycle Cost (LCC) for the Shuttle, but no Engineering Management processes were exercised to provide control (only the DDT&E cost was tracked). These LCC objectives are all of the same importance as placing a mass in orbit and must all be managed by the same level of discipline. The NASA must do better to achieve the Presidential requirement of conducting/achieving a sustainable space exploration program. The major part of the space transportation LCC is the recurring or operational phase cost.

A major source of knowledge utilized by the SPST was a study conducted of the "shortfalls" of current space transportation systems (Space Shuttle) to determine and document the shortfalls that developed between initial requirements/objectives and the actual results achieved. The results of this study are included in this report. A major "lesson learned" from these activities is the importance of first clearly defining, flowing down, and controlling the "systems requirements" and maintaining control throughout the R&D Program. The SPST has emphasized the need to clearly define the "requirements" up front: that is the "what's" required of the desired space transportation system. To sum up this lesson learned, we must change the way we do business to avoid "doing what we always do and achieving what we always got". Therefore, we must change our Engineering Management processes to include a structured process to control those major operational functions that are major cost influences to provide the LCC controls required for a sustainable Space Exploration Program.

Recently the SPST developed a new approach for formulating "requirements" that will provide full accountability of all functions required to perform the planned space missions. The approach as described in this report was to develop a top-level functional systems breakdown structure, (Functional SBS) with modular sub sets, that may be utilized as a basis for defining the desired "functional requirements" in any space system. This process is intended to serve as a guide in development of the work breakdown structure (WBS), provide visibility of those technologies that need to be enabled to cover a required function, and help identify the personnel skills required to develop and operate the space transportation system for this very large and challenging National effort. This Functional SBS covers all transportation elements on earth, the moon and mars including any orbiting operational space nodes if deemed necessary.

Another study performed by the SPST was a "bottoms-up" analysis as to why past programs weren't achieving the desired functional criteria: "what has impeded or prevented the application of good systems engineering and management's successful implementation of the approaches/processes addressed in this report?" It was found that there are several reasons for the impediments: lack of overall integration (stove-piping or optimizing at the single function level), inappropriate starting technology level, the lack of sufficient Engineering Management processes, and that many of the systems engineering requirements (needs), were "boring" not stimulating (not sexy). This indicates that major improvements in discipline must be rigorously imposed on the system engineering and design processes by the program managers.

The thrust of this was to respond to these insights gained in the analysis/studies referred to in this report and focus on developing the needed engineering management processes that will be required for NASA to achieve a sustainable space exploration program by controlling the space transportation system's LCC.

6.0 Conclusions

Based on study and analysis of several space programs including the Space Shuttle by the SPST, it is clear that past and current efforts to control life cycle costs have been inadequate and ineffective.

The "lesson learned" from these studies is that much improved, innovative processes must be developed and rigorously applied to adequately control life cycle costs. These improved/innovative process need to be enforced by the Program Managers throughout the design development, production and operation of the space systems that will be required for the Space Exploration Initiative missions.

It is believed that the improved life cycle control processes developed by the SPST and presented in this report will provide the necessary cost controls when properly applied in the future advanced systems.

7.0 Recommendations

The SPST is recommending NASA adopt the proven methods of controlling weight and performance and applying them to controlling cost.

The SPST recommends that the Program Analysis and Evaluation Office endorse the approach and procedures to life cycle costs assessment control described in this report. Further the SPST recommends that these new approaches and procedures be implemented within the current planning of the Space Exploration Program Missions.

We emphasize these recommendations, because, the Space Exploration Program must not only be "affordable" but "sustainable". This requires close control of life cycle costs within established budgets.

The SPST recognizes that it is not an easy task to fully understand the several new life cycle control processes and their value as presented in this report, and especially how to introduce them into current on going planning processes. Therefore, we propose that the SPST could provide a support role to the Program Analysis and Evaluation Office to "make this happen" by working with ESMD personnel to develop the metric values for these parameters being proposed. There are several ways to accomplish this, including direct frequent interface, via telecom, but also by Technical Interchange Meetings (TIMs) or even "workshops" dedicated to the education and implementation of these new processes that the Program Analysis and Evaluation office and the SPST could jointly organize and conduct.

Also, it should be noted that this approach offers the potential for broader education and utilization of these valuable life cycle costs control process: possible, through the NASA Outreach Program.

The Space Propulsion Synergy Team is quite unique in its organization, membership and capability of addressing this objective. It was chartered by NASA over a decade ago and has a diversified membership of retired and active senior engineers, managers and scientist from industry, government and academia who have a wealth of "hands on" hardware and management experience. The SPST was and continues to be dedicated to the development and operation, of safe, dependable, affordable and sustainable space transportation systems. Coordination and logistics costs for maintaining and accessing this capability require SPST to seek some NASA funding. The SPST therefore requests NASA accept a formal proposal for SPST support in implementing the details suggested in this report.

Appendix I

Space Shuttle Shortfalls Assessment Results

The SPST Functional Requirements Subteam prepared the following table which shows the current capabilities of the Space Shuttle and the Critical Shortfalls relative to the initial space shuttle requirements. It is the SPST position that NASA must understand the shortfalls of the current Space Shuttle before NASA can correct these shortfalls or design them out of the next generations of space launch vehicles.

SUMMARY OVERVIEW
Current RLV Space Transportation Systems Shortfalls Assessment

		Space Shuttle		Critical Shortfalls Relative to Requirements
Attribute I D.	**Program Objectives and Desired Attributes needed to Correct Shortfalls of Current Systems**	**Target Value**	**Actual Achieved**	**Critical Shortfalls Relative to Requirements**
D 2.1	1. Program STS Design Life Propulsion Main Engine Life	10 years or 100 flts/veh. 55 starts/Depot cycle.	20+ years, but only 30 flts/veh. Max., but still counting After 20+ years ops, SSME depot cycle 20, LO_2 turbo-pumps 10 & fuel turbo-pumps 3 flts	The Space Shuttle was intended to fly 10 flights per year each without extensive maintenance and recertification between flights (160 hour turnaround). Design complexity and hardware dependability only permits less than 3 flights per year. Avg. 100 components replacement plus ~ 400 expendable or limited life parts. The SSME initial design life was 55 flights before entering depot cycle, but limited life/dependable hardware has required extensive labor, time, and engine depot support, e.g., resulting in high cost per flight. Application must be well understood so that the reliability requirements flow-down supports the design life after balancing the requirement with safety and maintainability. Also the reliability requirement must be demonstrated by testing and improved until the requirement is met.

Attribute I D.	Program Objectives and Desired Attributes needed to Correct Shortfalls of Current Systems	Target Value	Actual Achieved	Critical Shortfalls Relative to Requirements
A 1.2 S 4.3	2. Recurring cost: All processes and operations must be compatible with environmental regulations and laws	$100.00/lb to orbit No Requirement documented? Today's regulations were not established during the Shuttle concept and DDT&E phases and it was assumed NASA would abide by the country's laws.	~ $10,000.00/lb to orbit Actual Shuttle recurring cost over the total 21 operating years = ~ $57.876 Billion. Stringent Environmental /OSHA requirements have been imposed since Shuttle ATP	The initial design recurring costs were $100.00/lb to LEO which was based on achieving an allocated 40 launches per year using 4 orbiters flying 65,000 lbs per flight. Most flights do not fly at maximum capacity and the 10 flights per year per each orbiter was not achievable because of complexity (optimizing at the sub-system level "stove-piping" and not at the overall STS systems level) and poor dependability of total system. STS Program didn't include cost allowances for changes in the environmental laws.

Attribute I D.	Program Objectives and Desired Attributes needed to Correct Shortfalls of Current Systems	Target Value	Actual Achieved	Critical Shortfalls Relative to Requirements
A 1.1/ P 5.2, P 5.3 & 5.4 A 1.7	3. Non-recurring cost:(DDT&E and Acquisition) LCC must be well defined and understood by analysis without any allocations/assumptions so that the business case closes All technologies must be matured at the TRL-6 level or above and options must be available as backup where risk is moderate or above prior to the start of acquisition.	$5.0 Billion The targeted NRC was $5 billion and the Recurring target was $6.5 million/flight = to $2.6 billion in 10 yrs. Or a total LCC = to $7.6 billion. Assumptions were 65,000 lbs to orbit each flight, 10 flights/orbiter or 40 flights/yr at $100/lb to orbit. DDT&E schedule and cost risks were not considered a necessity as we were still working to the Apollo paradigm.	Shuttle NRC (DDT&E) = $15 billion and the RCC average is ~$2.756 billion/yr. Therefore, the intended 10 year program LCC would have = $42.56 billion. But the Actual Shuttle recurring cost over the total 21operating years = ~ $57.876 B. Or a total LCC = $72.876 B. These actual cost do not include any R&T cost prior to the STS ATP (1-5-72), e.g., SSME, TPS, etc. Five Major System's Technologies less than TRL-6 level at ATP: High Pressure LO_2/LH_2 Staged Combustion Rocket Engine, Vehicle TPS, Large Solid Rocket Motor Nozzle Flex Seal TVC system, Ice/frostless cryogenic tanks, & 100% digital flight/ground control systems	The initial design non-recurring cost estimate were $5.0B based on an allocated DDT&E schedule. Due to non-mature major technologies (HP LH2/LO2 staged combustion rocket engine, re-entry TPS, Solid rocket flex nozzle seal, Ice/frost less cryogenic tanks, and 100% digital flight/ground control systems), schedule was overrun 2 years because much unplanned technology maturation was required. Started the development with high risk schedule for technology maturation without providing a margin in cost or schedule to account for this high risk approach. There were no requirements or policy documented towards the use of mature or non-mature technologies. A very large shortfall exist in the LCC projections because they were based on allocations that never came into fruition, e.g., 65,000lbs to orbit each flight and 40 launches per year using 4 orbiters. Also the DDT&E cost projection had a large shortfall because of the immature technologies causing an extended schedule for this activity. Allocations of the operational functions could not be met because there was no engineering management processes in place to provide the necessary control required.

Attribute I D.	Program Objectives and Desired Attributes needed to Correct Shortfalls of Current Systems	Target Value	Actual Achieved	Critical Shortfalls Relative to Requirements
R 3.2 R 3.1 &3.9 D 2.6	4. Each vehicle flight rate: Fleet flight rate: Vehicle turnaround time: System performance to LEO Materials, fluids, and design properties and limitations well understood through failure with narrow tolerances	10 flights/yr. 40 flights/yr. at ETR 160 hours 65,000 lbs at ETR @ 28.8 degrees and 100 nmi Considered as over constraining and would have driven up the DDT&E cost considerably.	2.5-3 flights/yr. 10 flights/yr. 1296 hours Min. 55,000 lbs at ETR @ 28.8 degrees and 100 nmi Because the limits were not known, operational controls provided margins to avoid unplanned events. Performance carried an extra margin to allow for these uncertainties.	The initial design allocation for turnaround was 160 hours landing to re-launch. The initial design flight rate was 10 flights per year for each orbiter, but because design requires the functional integrity to be broken each flight to perform the turnaround, ~ 400 expendable or limited life parts to be replaced, and ~ 100 failed components to be replace during the turnaround operation, and extensive servicing (too many different fluids & too many interfaces along with the extensive support infrastructure) required the achievable flight rate is just above 2 per year. Because the integrity of systems are compromised to provide for parts change-out and the support turnaround operations, the STS must be re-certified for each flight. The shortfall in payload mass capacity was a result of lack of sufficient margins in performance of each variable, e.g., orbiter over weight, SSME Isp low, and the drive to keep the ET production cost low. Example of cost to remove ET weight was and additional $20,000,000. /unit for a 6,000 pound reduction. Program objectives were compromised because of the added limitations do to uncertainties.

Attribute I D.	Program Objectives and Desired Attributes needed to Correct Shortfalls of Current Systems	Target Value	Actual Achieved	Critical Shortfalls Relative to Requirements
S 4.2 R 3.1 &3.9 D 2.5 S 4.1 &4.2	5. Space flight rescue time: Launch Availability: Vehicle/System terminal countdown: Launch on time (No launch scrubs) Flight abort during ascent: No Loss of Crew Flight abort from orbit: No Loss of Crew	24 hour notice to launch from standby status (VAB/T-0) VAB rollout including payload change-out at the pad, MPS propellant loading, crew ingress, final close-out checks and terminal count. 2 hours No Requirement documented except 24 hr. notice to launch for space rescue & military needs. Designed for RTLS/ATO/AOA KSC prime, EAFB secondary, & several contingencies	Not capable, but now being considered again since Columbia event. 14 Work Days at the Pad is best case before STS-51L and 19 Work Days at the Pad has been demonstrated after the STS-51L event. 8 hours plus 65 of the 113 missions launched the day scheduled (57.5%). Of the 48 launch scrubs, 13 were weather related (27%) However, some missions were scrubbed more than once/mission. Did not demonstrate RTLS or TAL's and ATO was required only once, but did not result in an aborted operation. 3 landing sites used: (KSC, EAFB, & White Sands)	The requirement for the 2 hour terminal countdown was deferred because of the added DDT&E cost to provide the automation for crew egress and MPS Lox transfer capacity needed and the lack of meeting the fleet flight rate. There was no requirement against reliability to accomplish either the launch on time or meet the 24 hour notice to launch for a space rescue. Not considered as a need to provide any control and was considered as over constraining. Requirements flow-down were not developed, implemented and controlled to provide this capability. Lack of major system integration resulted into too many flight/ground service interfaces, controlled access conditions and extensive time consuming operations. Abort during ascent operations required the SRB's to burn to completion and failure occurred with the SRB resulting in the loss of the orbiter (099) and its crew. Therefore, abort during ascent did not cover all critical failure modes. No abort was provided during the descent phase and an orbiter (102) and its crew were lost during re-entry. The STS vehicle reliability wasn't sufficient to support the abort modes required.

Attribute I D.	Program Objectives and Desired Attributes needed to Correct Shortfalls of Current Systems	Target Value	Actual Achieved	Critical Shortfalls Relative to Requirements
D 2.1 **D 2.2** **D 2.3** **D 2.4** **&** **S 4.1** **&** **R 3.1**	6. STS Dependability/Safety Loss of Vehicle Flight system program reliability: Mission reliability: Flight environment: Launch & Landing	All flight vehicle subsystems (except primary structure, thermal protection system, a pressure vessels) shall be established on an individual subsystems basis, but shall not be less than fail-safe. Safety, reliability, and maintainability were controlled separately by NHB 5300.4 (lD-1), August 1974, or 0.98 for 100 missions of each orbiter or 500 missions total for fleet of 5 orbiters. Requirement for 95 percentile natural environment expected at operational locations	Program has lost 14 flight crew and 2 ground members and two orbiters, e.g., 0.964 for the Orbiter and 0..962 for the SRB and a mission Reliability of ~0.96 7 mile visibility & no rain	Program did not consider cost impact of vehicle loss accompanied with down time for the investigation and corrective action required for re-flight. Importance of loss of vehicle and the resultant impact on the program wasn't considered with proper risk reduction actions. Target metric value for reliability was deficient in determining its overall judgment in importance. No requirements were established for loss of flight or ground crew members and the impact of insufficient component reliability was not considered and understood. Target metric value was also deficient in determining its overall impact on the maintainability burden (plus large depot maintenance and supply chain support) resulting in reduced flight rate and increased cost per flight. Because the recurring cost per flight was not controlled, the mission reliability importance was not understood. Orbiter TPS cannot function in design environment without damage. TPS needs to be more robust to be in compliance with requirements and to avoid launch and landing scrub/delayed operations. This lack of robustness attributed to the loss of an orbiter and 7 crew members.

Attribute I D.	Program Objectives and Desired Attributes needed to Correct Shortfalls of Current Systems	Target Value	Actual Achieved	Critical Shortfalls Relative to Requirements
R 3.7 **D 2.1**	7. STS Dependability/Safety/ Maintainability: Component replacement time or MTTR:	Shuttle orbiter was designed for 100 flights or 10 years without planned maintenance. No other Direct Requirement other than (160 hours turnaround) Except the Shuttle SSME 55 starts/Depot cycle. SRB was to be recovered and refurbished every flight.	Replace Avg. of 100 components/flight unplanned & best case orbiter turnaround is ~ 960 hrs. There are many limited life components on the Shuttle orbiter, e.g., ~ 200 expendable ordinance items and ~ 200 other limited life items to track & replace. Also after 20+ years of ops, SSME depot cycle is every 20 flights, with the LO_2 turbo-pumps after every 10 & fuel turbo-pumps after every 3 flights Example of SSME MTTR Controller replacement during scrub-turnaround: Up to 5 days or 80 Hrs.	Only requirement was the 160 hour turnaround and maintainability design efforts were dropped early in the DDT&E phase because of cost overruns and schedule concerns. Critical component redundancy was implemented with component reliability levels that ignored the resultant maintainability burden. This lack of controlled maintainability requirements (accessibility, intrusive nature of most of the hardware and no automated functional verification) has contributed to the large resultant cost per flight and the low flight rate. Controlled maintainability requirements properly balanced with safety and reliability using existing methodologies is major shortfall in the STS program and has contributed to the large resultant cost per flight and the low flight rate.

Attribute I D.	**Program Objectives and Desired Attributes needed to Correct Shortfalls of Current Systems**	**Target Value**	**Actual Achieved**	**Critical Shortfalls Relative to Requirements**
R 3.9/ A 1.5	8. Total number of assembly functions required at the launch site between flights	The shuttle initial design requirement provided an allocation of 34 hours of the 160 turnaround for the space vehicle assembly. Also a 40 flights/yr. fleet flight rate with 4 vehicle fleet size.	The two SRB stages are completely assembled from scratch at the launch site for each launch on the MLP, a new ET is received and integrated into the SRB/MLP stack, with the Orbiter being integrated as the final step of building the flight vehicle. The Orbiter requires re-configuration for each unique payload structural attachment as well as providing unique airborne support equipment to service the payload after installation into the Space Vehicle.	The large SRB vehicle element concept does not lend to the objectives of an RLV that achieves a 40 launch per year flight rate as it must be built-up at the launch site and the recovery operations are more like salvage and reconstruction operations. Design concept choice was inappropriate for the objective of the space transportation system.
R 3.9/ A 1.5 D 2.1	9. Total number of expendable items/components included in the reusable system design	Objective was to provide an RLV with a 160 hours turnaround capability that could fly 40 time a year with a fleet of 4 orbiters.	~ 200 ordinance items replaced every flight and ~ 200 other one-flight limited life items on the orbiter plus the expendable ET and much expendable hardware on the SRB's.	Designers and program managers loss sight of the objective to build an RLV because of an overriding focus on meeting the performance requirements in the absence of any other structured engineering management processes used to control such thing as life cycle cost or any of the other program level one objectives.

Attribute I D.	Program Objectives and Desired Attributes needed to Correct Shortfalls of Current Systems	Target Value	Actual Achieved	Critical Shortfalls Relative to Requirements
R 3.9/ A 1.5/ R 3.6	10. Total number of sub-systems requiring servicing with dedicated ground systems, e.g., number of different Fluids, number of different Electrical supplies, etc. Easily Supportable (minimum support infrastructure required) and must be compatible with all LCC requirements by analysis without any assumptions	Objective was to provide an RLV with a 160 hours turnaround capability that could fly 40 time a year with a fleet of 4 orbiters and with a 24 hr. notice to launch capability to accommodate rescue.	Shuttle System requires the tracking and managing of ~ 54 different fluids and ~ 30 unique fluids are serviced every flight. Many of these fluids are common from one discipline to another, which require separate umbilicals, as they do not share storage on the vehicle. The Shuttle has ten (10) major sub-system disciplines that require fluid servicing between flights with several unique support systems that also require servicing every flight. The total of 102 dedicated sub-systems requires servicing for each flight. Seventeen (17) dedicated electrical power supplies that required support and service each flight.	STS cost analysis was shallow and was based on allocations with no follow-up in establishing requirements flow-down to assure compliance in meeting these objectives. LCC analysis must be realistic and based on the functional requirements along with assurance the objectives can be met. Not considered was a need to provide any control that would have been considered over constraining. Designers and program managers loss sight of the objective to build an RLV because of an overriding focus on meeting the performance requirements in the absence of any other structured engineering management processes used to control such thing as life cycle cost or any of the other program level one objectives. Also the STS was optimized at the sub-system level (stove-pipe approach) and not at the overall integrated level. Electrical functions are custom managed on the ground and uniquely provided through separate umbilicals instead of simplifying the flight to ground interface functions by providing the electrical management on the vehicle. Major shortfall is the need for structured engineering management process (like the one used by Shuttle to control weight/performance) to provide controls that would drive overall system integration.

Attribute I D.	Program Objectives and Desired Attributes needed to Correct Shortfalls of Current Systems	Target Value	Actual Achieved	Critical Shortfalls Relative to Requirements
R 3.9/ A 1.5/ R 3.6	10. Total number of sub-systems requiring servicing with dedicated ground systems, e.g., number of different Fluids, number of different Electrical supplies, etc. Easily Supportable (minimum support infrastructure required) and must be compatible with all LCC requirements by analysis without any assumptions *Con't*		Data bus and communication systems as well as unique instrumentation have not been accounted for in this assessment. Orbiter element alone has 402 functional interfaces: Propulsion discipline has 236 of which an SSME has 25/engine documented in the formal structured flight to ground interface (ICD) system for the single ground turnaround facility station (ICD-2-1A002). Note: The orbiter element has ten (10) more facility station ICD's at the launch site.	

Attribute I D.	**Program Objectives and Desired Attributes needed to Correct Shortfalls of Current Systems**	**Target Value**	**Actual Achieved**	**Critical Shortfalls Relative to Requirements**
R 3.6 R 3.9 A 1.5	11. Degree of custom build required to support each mission Total number of manual functions required to determine and control critical flight functions, e.g., CG, fluid residuals content & purity, functionality of primary and backup system hardware Vehicle, payload, and ground systems integration functions must be compatible with all LCC requirements by analysis without any assumptions.	The shuttle initial design requirement provided an allocation of 96 hours of the 160 turnaround for the orbiter turnaround including the payload installation verification. Also a 40 flights/yr. fleet flight rate with 4 vehicle fleet size.	Each different payload requires the Orbiter to be custom built to support the structural load and any servicing requires special airborne support equipment to be installed and verified along with optimizing the mass impact on the payload for these services. Also flight software must be custom built for each mission.	Standardized payload accommodations were not provided by the STS; therefore, all electrical, mechanical and fluids accommodations are custom designed for every mission. Also standardized mission planning for payload mass, orbit destinations, etc. were not provided; therefore, each mission is planned as a custom mission. There were no structured engineering management processes put in place to provide constraints or to limit these functional requirements for each flight. There was no automated functional verification capability (IVHM) provided to reduce the labor intensiveness of the task. STS cost analysis was shallow and was based on allocations with no follow-up in establishing requirements flow-down to assure compliance in meeting these objectives. LCC analysis must be realistic and based on the functional requirements along with assurance the objectives would be met.

Attribute I D.	Program Objectives and Desired Attributes needed to Correct Shortfalls of Current Systems	Target Value	Actual Achieved	Critical Shortfalls Relative to Requirements
R 3.6 **R 3.9** **A 1.5**	11. Degree of custom build required to support each mission Total number of manual functions required to determine and control critical flight functions, e.g., CG, fluid residuals content & purity, functionality of primary and backup system hardware Vehicle, payload, and ground systems integration functions must be compatible with all LCC requirements by analysis without any assumptions. *Con't*		Orbiter element alone has 402 functional interfaces of which the Propulsion discipline alone has 236 of which the SSME has 25/engine documented in the formal structured flight to ground interface (ICD) system for the single ground turnaround facility station (ICD-2-1A002) – for the vehicle to ground design and operations activities. Note: The orbiter element has ten (10) more facility station ICD's at the launch site. The above is an example of all major flight element interface support requirements as the SRB's have 16 safety driven functional requirements and 28 safety driven limited access control requirements.	

R 3.1 &3.8	12. Mission Planning Cycle	Was considered within the 40 flights/yr. with 4 vehicle fleet and the 24 hr. notice to launch requirement.	400 day typical cycle	Standardized payload accommodations were not provided by the STS; therefore, all electrical, mechanical and fluids accommodations are custom designed for every mission. Also standardized mission planning for payload mass, orbit destinations, etc. were not provided; therefore, each mission is planned as a custom mission.

Appendix II

Space Shuttle Level I and II Program Requirements Documentation excerpts

The following are the most pertinent excerpts.

1.0 INTRODUCTION.

1.1 PURPOSE AND SCOPE. The purpose of this document is to establish the Level I program requirements for the Space Shuttle Program. These are requirements established by the Director of the Space Shuttle Program as necessary to achieve the objective of the Space Shuttle Program, namely to: (a) reduce substantially the cost of space operations, and (b) provide a capability designed to support a wide range of scientific, defense, and commercial uses.

All Space Shuttle Program planning and direction of NASA Centers should be in accord with the requirements stated herein unless specific exception is approved in writing as an addendum to those Space Shuttle requirements by the Director of the Space Shuttle Program.

2.0 SPACE SHUTTLE SYSTEM REQUIREMENTS.

2.1 DESCRIPTION. The Space Shuttle System flight hardware shall consist of a reusable orbiter Vehicle including installed main engines, an expendable External Tank and reusable Solid Rocket Boosters which burn in parallel with the main engines. The Orbiter Vehicle shall be capable of crossrange maneuvering during entry, aerodynamic flight and horizontal landing.

2.2 OPERATING LIFE. As a design objective, the Orbiter Vehicle should be capable of use for a minimum of 10 years, and capable of low cost refurbishment and maintenance for as many as 500 reuses.

2.4 PAYLOAD MASS ACCOMMODATION. The Space Shuttle System shall be capable of operating within the up payload range from zero to 65,000 lbs. (29,483 kg) for nominal launches and abort modes. Nominal down payloads shall be limited to 32,000 lbs. (14,515 kg). The Orbiter Vehicle payload C.G. limits for longitudinal, vertical and lateral axes are shown in Figures 2-1, 2-2 and 2-3.

2.8 REDUNDANCY. The redundancy requirements for all flight vehicle subsystems (except primary structure, thermal protection system, and pressure vessels) shall be established on an individual subsystems basis, but shall not be less than fail-safe. "Fail-safe, is defined as the ability to sustain a failure and retain the capability to successfully terminate the mission. Redundant systems shall be designed so that their operational status can be verified during ground turnaround and to the maximum extent possible while in flight.

2.18 SAFETY, RELIABILITY, MAINTAINABILITY AND QUALITY. The provisions of NHB 5300.4 (lD-1), August 1974. "Safety, Reliability, Maintainability and Quality Provisions for the Space Shuttle Program" will apply for the Space Shuttle Program.

2.22 FACILITIES AND SUPPORT EQUIPMENT COMMONALITY. A major goal of the Space Shuttle Program shall be to minimize the national investment in launch facilities, GSE, and other support equipment (including the launch processing system and associated software) through maximization of the commonality of requirements, design and procurement of these items between KSC and VAFB. The specification and design of operational facilities, support equipment and procedures at KSC shall include maximum consideration of the requirements and design constraints inherent in operations at VAFB. VAFB design shall make maximum practical use of the operating procedures and ground and other support equipment developed for KSC.

3.0 OPERATIONAL REQUIREMENTS.

3.1 GENERAL. The Space Shuttle System shall be designed to accomplish a wide variety of missions.

The Shuttle System weight carrying capability into orbit shall be based on the performance required to execute mission 3A. The equivalent maximum performance is shown in Figures 3-1 and 3-2 for the range of inclinations and altitudes indicated. The payload capability curves assume a simple deployment mission with no rendezvous, 22 fps (6.9 m/sec) OMS Reserves, 4,500 lbs. (2,041 kg) of RCS propellant, and direct deorbit. (Reentry performance restrictions are addressed in Par 2.4. Detailed Shuttle System performance questions should be addressed to the JSC Shuttle Program office).

Space Shuttle missions will involve direct delivery of payloads to specified low Earth orbits; placement of payloads and transfer stages in parking orbits for subsequent transfer to other orbits; rendezvous and station keeping with detached payloads for on-orbit checkout; return of payloads to Earth from a specified orbit; and provisions for routine and special support to space activities, such as sortie missions, rescue, repair, maintenance, servicing, assembly, disassembly and docking

3.2 REFERENCE MISSIONS.

3.2.1 Design Reference Missions. These missions shall be used in conjunction with the other requirements specified herein to size the Space Shuttle System. For performance comparison)s, Mission 1 will be launched from Kennedy space center (KSC) into a 50 by 100 n. mi. (93xl65 km) insertion orbit, and Mission 3 will be launched into the same insertion orbit from the Vandenberg AFB.

a. Mission 1. Mission I is a payload delivery mission to a 150 n. mi. (278 km) circular orbit. The mission will be launched due east and requires a payload capability of

65,000 lbs. (29,483 kg). The Boost phase shall provide insertion into an orbit with a minimum apogee of 100 n. mi. (185 km), as measured above the Earth's mean equatorial radius. The purpose of this mission is assumed to be placement of 65,000 lb. (29,483 kg) satellite and/or retrieval of a 32,000 lb. (14,515 kg) satellite. The Orbiter Vehicle orbit translational Delta V requirements in excess of a 50 by 100 n. mi. (93 x l85 km) reference orbit are 650 ft/sec (198 m/sec) from the Orbital Maneuver Subsystem (OMS) and 100 ft/sec (30 m/sec) from the RCS.

b. Mission 2. (Deleted).

c. Mission 3. Mission 3 shall consist of two missions, one for payload delivery and one for payload retrieval. This is a 3-day, 2-man mission.

Mission 3(A). This mission is a payload delivery mission to an orbit of 104 degrees inclination and return to the launch site. The boost phase shall provide insertion into an orbit with a minimum apogee of 100 n. mi. (185 km) as measured above the Earth's equatorial radius. The Orbiter Vehicle on-orbit translation Delta V requirements in excess of a 50 by 100 n. mi. (93 X 185 km) reference orbit are 250 ft/sec (76 a/sec) from the orbital Maneuver Subsystem (OMS) and 100 ft/sec (30 m/sec) from the RCS. The ascent payload requirement is 32,000 lbs. (14,515 kg). For mission performance and consumables analysis, a return payload of 2,500 lbs. (1134 kg) will be assumed (the 2500 lbs. (1134 kg) is included in the 32,000 lbs. (14,515 kg) ascent payload weight).
Mission 3(B). This mission is a payload return mission from a 100 n. mi. (185 km) circular orbit. it 104 degrees inclination and return to the launch site. The return payload weight is 25,000 lbs. (11,340 kg). For mission performance and consumables analysis, an ascent payload of 2,500 lbs. (1134 kg) will be assumed (the 2,500 lbs. (1134 kg) is included in the 25,000 lbs. (11,340 kg) return payload weight). The Orbiter Vehicle on-orbit translation Delta V requirement in excess of a 100 n. mi. (185 km) circular orbit is 425 ft/sec (130 a/sec) from the OMS. The translational Delta V requirement from the RCS is 190 ft/sec (58 m/sec).

3.2.2 Performance Reference Missions. These missions shall be used in conjunction with the other requirements specified herein to assess the performance capabilities of the Space Shuttle System, as sized by the design reference missions, to assure that the mission requirements will be met.

a. Mission 4. This mission is a payload delivery an(I retrieval mission launched from the Vandenberg AFB Launch Site to a final inclination of 96 degrees in a 150 n. mi. (277.8km) circular orbit as measured above the Earth's equatorial radius. The ascent payload requirement is 32,000 lbs. (14,525 kg). The return payload requirement is 25,000 lbs. (11,340 kg). The Orbiter vehicle on-orbit translational Delta V requirement, including post MECO insertion burn and deorbit, is a total of 1,050 ft/sec (321 m/sec). The onboard RCS propellant tanks will be fully loaded at launch.

NSTS 07700 VOLUME X – BOOK 1 REVISION M NOVEMBER 10, 1998

REPLACES NSTS 07700, VOLUME X REVISION L
FLIGHT AND GROUND
SYSTEM SPECIFICATION
BOOK 1 REQUIREMENTS
Lyndon B. Johnson Space Center
Houston, Texas 77058
National Aeronautics and
Space Administration
SPACE SHUTTLE

3.0 REQUIREMENTS
3.1 SHUTTLE SYSTEM DEFINITION
3.1.1 Shuttle System Elements
3.1.3 Shuttle System Weight and Performance Control
For all elements, the nominal weights shall be based on inert weights (dry plus closedloop fluids) and are defined in NSTS 09095, Space Shuttle Systems Weight and Performance. Planning weights for consumables, propellants, personnel, and the payload are specified also in the referenced document.

3.1.3.1.2.1 Orbiter Design Control Weights
The OV-102, -103, -104, and -105 nominal design control weights are 160,289 pounds, 155,701 pounds, 154,910 pounds, and 155,707 pounds, respectively. These nominal design control weights include all approved and projected Orbiter modifications, anticipated weight growth projections, and with the exception of OV-102, the weight of the external airlock and Orbiter Docking System (ODS). The allowable flight-to-flight manufacturing variation for each Orbiter is _550 pounds. The Orbiter maximum design control weight is the nominal design control weight plus the manufacturing variations. The control weight for the Orbiter separation/attach hardware installed on the external tank is 64 pounds. A detailed listing of these modifications and projections is provided in NSTS 09095.

3.1.3.1.2.2 External Tank (ET) and Main Propulsion Subsystem (MPS) Design Control Weights

3.1.3.1.2.2.1 ET Design Control Weight
The Lightweight (LWT) ET nominal design control weight is 65,449 pounds. In order to support the ISS, the Super Lightweight Tank (SLWT) nominal design control weight is 58,505 pounds. The ET maximum design control weight is the nominal design control weight plus the manufacturing variations. These weights specifically exclude Orbiter and SRB separation/attach hardware that is installed on the tank. The allowable flight to-flight manufacturing variation for each tank is _511 pounds. This manufacturing variation is for mission planning purposes and shall not be verified.

3.1.3.1.2.2.3 SLWT MPS Design Control Weight

The usable LH2 and Liquid Oxygen (LOX) minimum design control weights are specified in NSTS 08209, Shuttle Systems Design Criteria, Volume I, Shuttle Performance Assessment Databook, Table 4.5.7.

3.1.3.1.2.3 Solid Rocket Booster (SRB)

3.1.3.1.2.3.1 SRB Design Control Weight
The SRB nominal design control weight is 1,299,550 pounds. This weight consists of 149,360 pounds motor inert weight, 44,060 pounds subsystem inert, and 1,106,130 pounds motor propellant. The allowable flight-to-flight manufacturing variation for each Volume X - Book 1 Revision M 3-4 CHANGE NO. 290 of these values is _1,270, _560, and _2,323 pounds, respectively. The subsystem and motor inert hardware shall not exceed the nominal design control weight plus the inert manufacturing variations. The motor propellant shall not be less than the nominal design control weight minus the propellant manufacturing variations. The RSRM control weight margin (combined motor inert and propellant) is +10 pounds of equivalent payload. The SRB subsystem inert control weight includes a control weight margin of +50 pounds per SRB (10 pounds of equivalent payload performance weight). The control
weight for the SRB separation/attach hardware installed on the ET is 829 pounds.

3.1.3.1.2.4 SSMEs Design Control Weights and Performance Characteristics

3.1.3.1.2.4.3 Block II Design Control Weights and Performance Characteristics
The Block II SSME nominal design control weight is 7,748 pounds. The allowable unit-to-unit manufacturing variation for each SSME is +65/-111 pounds. The SSME maximum design control weight is the nominal design control weight plus the manufacturing variations. The operating characteristics shall be as specified in NSTS 08209, Volume I, Table 5.1. Volume X - Book 1 Revision M 3-5 CHANGE NO. 265

3.1.3.1.2.5 Cargo Integration Equipment Configuration and Design Control Weight The total maximum design control weight is 2,267 pounds for the cargo integration equipment (excluding the payload attach hardware) required to support the generic ISS reference mission defined in Paragraph 3.2.1.1.3.8. The weight of all unique cargo integration hardware is chargeable to the payload control weight and is not included in the weights provided in this paragraph. An item by item listing of the generic integration equipment with weights for each item is provided in NSTS 09095.

3.1.3.1.2.6 Crew and Cabin Manifest Equipment Design Control Weight

3.1.3.1.2.6.1 Crew Equipment (Core) Design Control Weight
The core crew equipment maximum design control weight for a 5-crew/7-day Space Shuttle or ISS reference mission is 4,611 pounds. A matrix providing the weights for various combinations of crew size and duration as well as a detailed listing of equipment, provisions, and installations from which these weights are compiled is provided in NSTS 09095, Appendix 2. The weight of all lockers used by the payload (locker shell and

contents) is chargeable to the payload control weight and is not included in the weights provided in this paragraph.

3.1.3.1.2.6.2 Cabin Manifest Equipment Design Control Weight

The generic cabin equipment maximum design control weight for the 5-crew/7-day ISS reference mission is 74 pounds. A detailed listing of equipment, provisions, and installations from which this weight is compiled is provided in NSTS 09095, Appendix 2. The weight of all lockers used by the payload (locker shell and contents) is chargeable to the payload control weight and is not included in the weight provided in this paragraph.

3.1.3.1.2.7 Consumables

3.1.3.1.2.7.1 Propulsive Consumables

The maximum design control weight for propellant loading required to support the generic ISS mission defined in Paragraph 3.2.1.1.3.8 for the OMS, aft Reaction Control Subsystem (RCS), and forward RCS tanks are 22,930 pounds, 4,970 pounds, and 1,912 pounds, respectively. The OMS load includes 4,000 pounds allocated for the OMS assist.

3.1.3.1.2.7.2 Non-Propulsive Consumables (NPC)

The total maximum design control weight is 5,032 pounds for the NPC loading required to support the generic ISS reference mission defined in Paragraph 3.2.1.1.3.8.

Appendix III

An example of SPST Support of Spaceliner 100 Technologies Planning

1.0 Process

1.1 Functional Requirements Team

The primary purpose of this team (led by Russ Rhodes) was to define and prioritize the "functional requirements" of a space transportation system that has the potential of meeting the challenging goals NASA defined for an RLV/Gen 3 system. The RLV/Gen 3 goal was to have an "operational" transportation service by 2025-2030 which is 10,000 times "safer" and 100 times lower in operational costs than the current space shuttle SST. These "functional requirements" are "whats" the customer wants in an advanced space transportation service.

This team was also responsible for defining and prioritizing the "hows" i.e. how can a transportation system provide "what" the customer wants. The "hows" were identified by defining measurable criteria (technical/design and programmatic factors) that would support/correlate with the desired "attributes". These were required inputs to the "workshop" for defining, assessing, and prioritizing candidate technologies for an RLV/Gen 3.

A critical step was for the team to determine the level of improvement required in each "attribute". It was also necessary to have the customer, in this case ASTP, provide a weighting of the "attributes".

The pareto (prioritized list) of the programmatic factors utilized in the workshop assessment process is shown in Figure 1.

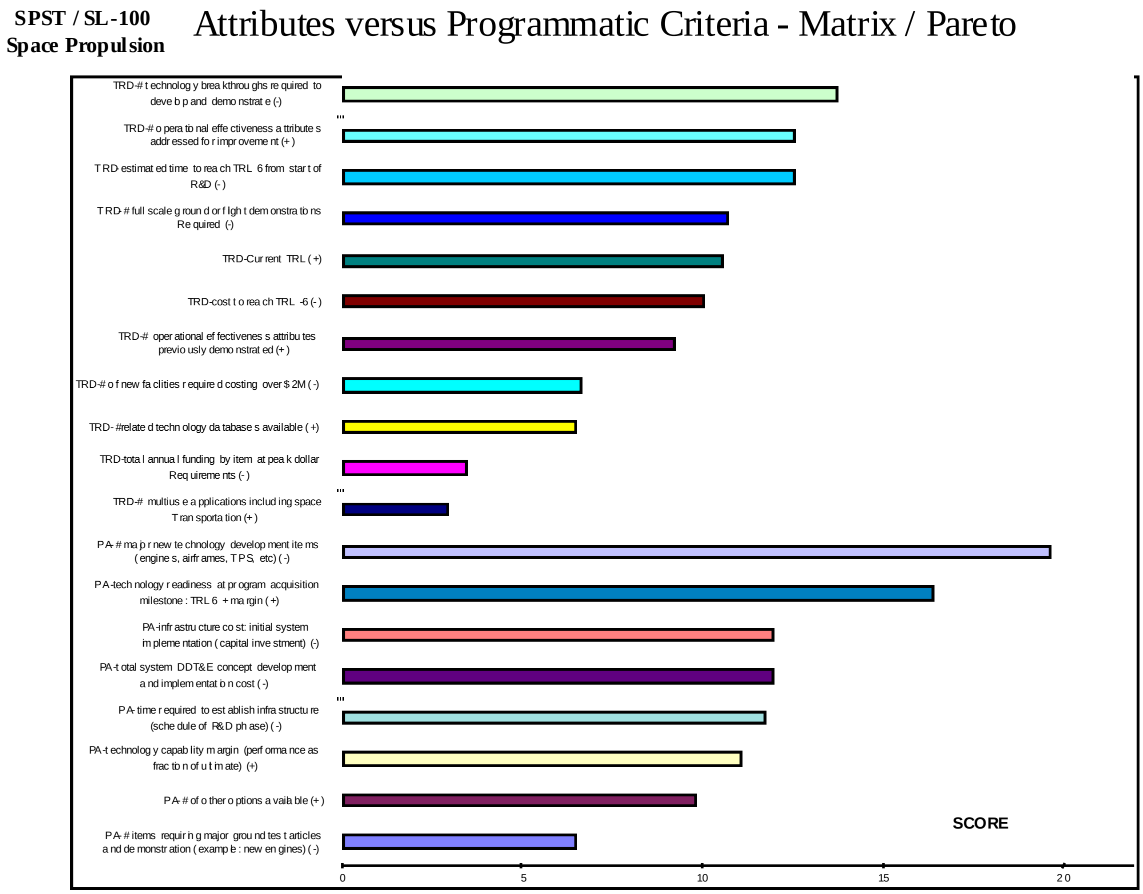

Figure 1

1.2 Transportation Architectures Team

The basic task of the SPST was to identify, define and prioritize propulsion system technologies that are critical to enabling the development and operation of a space transportation service capable of meeting the "challenging goals" that are embedded in NASA's Gen 3 safety and cost goals. However, it was necessary for the SPST task force to first broadly address this task at the transportation system level. Therefore, a transportation system Architecture Team (led by Keith Dayton) was formed to: (1) identify and define space transportation system architectures that have the potential of satisfying the RLV/Gen 3 functional requirements, and (2) identify and define the major system elements within these architectural concepts. The overall purpose is to provide the means of identifying the key propulsion related technologies to enable the development of an RLV/Gen 3 system.

The approach was to broadly address the system architectures required for the country (USA) to reach NASA defined, low cost access to space goals while increasing human space transportation safety. The Transportation Architecture Team was tasked with identifying the major elements of space transportation system architectures needed to get payloads (cargo and human) to and from Low Earth Orbit (LEO)) and beyond. These elements include several types of space transportation vehicles, as well as the required ground operational support infrastructure. The potential transportation service architectural concepts and payloads beyond LEO were included because they may have requirements that will impact the design of the earth to LEO vehicles (sometimes referred to as space trucks).

Also recognizing that the objective of this task was to identify and prioritize "propulsion" and "propulsion related" technologies, the focus of this team was on the roles that "propulsion" played in defining the various space transportation system vehicles. Therefore, for this specific activity the focus was on propulsion systems for earth to LEO transportation vehicles.

System elements applicable to the Gen3 RLVs were identified in terms of the overall vehicle concept configuration, staging, takeoff/landing approach, launch assist, number of propulsion stages, and propellants for both "earth to orbit" and "orbit to orbit" concepts. These concepts were then compared to the functional requirements and subjectively ranked to systematically screen the concepts. The objective of this assessment was to reveal how basic systems/techniques would support the functional requirements.

The results of the Architecture Team produced vehicles for the Gen3 Reusable Launch Vehicles in the time frame 2025-2030. The following classes of vehicle features were identified.

1. Propulsion elements such as chemical rocket engines, pulsed detonation rocket engines, rocket based combined cycles and turbine based combined cycle engine systems.

2. Single and two stage to orbit ETO trucks employing vertical or horizontal takeoff, horizontal or vertical landing, LOX/H2 and/or LOX/Hydrocarbon propellants; and launch assist (e.g., MagLev) or no launch assist.

3. There were no exotic propulsion systems evaluated in this study (ie, propellantless, beamed energy, etc) at the request of NASA's Advanced Space Transportation (ATPS) Office.

1.3 Technologies Identification Team

The primary objective of the Technology Team (led by Dan Levack) was to identify and define propulsion and "propulsion related" technologies that are candidates for inclusion in the SL100 technology budget for FY 2001 and beyond. More specifically these technologies would first become candidates in the SL100 Technology Assessment and Prioritization Workshop.

The RLV/Gen 3 Functional Requirements, and especially the design criteria and programmatic factors, are essentially the main drivers in identifying key SL100 candidate technologies. This team chose to use three available sources in identifying the candidate technologies. First the technologies identified by NASA during the summer of 1999, as candidates for an advanced space transportation system, were collected. From these were abstracted those that were "propulsion" or "propulsion related". This process reduced the list of technologies from 48 to 21. Interactions with the Architectures Team and discussions within Technologies Identification Team led to the inclusion of two additional technologies - Thrust Augmentation and Bridge to Space (Tether second stage). The net result was that 23 technologies were presented at the AHP workshop. They were grouped into three categories: Enabling/Generic Technologies, Flight Systems, and Ground Systems.

This team was responsible for identifying and assimilating candidate technologies and for the preparation of a "white paper", quad chart, briefing, and a criteria table on each of the candidate technologies. In some cases it was a Technology Team member that had the experience and expertise needed to prepare a "white paper". However, as was the case for many other technologies, it was necessary to request support from individuals/organizations outside of the team. In order to have consistency in the format and content of these technology "white papers" each author was provided with a template to use as a guide.

For each of the 23 technologies presented, certain information was available on a server at MSFC and is also available as a starting point for future workshops. Up to four items were available: a quad chart from a NASA exercise in the summer of 1999, a short briefing for the workshop, a "white paper", and a table of design criteria used for discrimination among technologies with comments regarding the particular technology in relation to these criteria. Not all four items were available for each technology and the depth of each item varied considerably from technology to technology.

1.4 Technologies Assessments and Prioritization Workshop Team

The Technologies Assessment and Prioritization Team (led by Dr. Pat Odom) was assigned the responsibility of: (1) defining the process to be used for prioritization of the identified candidate Spaceliner 100 propulsion technologies; (2) recruiting and arranging the participation of an appropriate group of expert evaluators to exercise the process; and (3) planning and facilitating the prioritization workshop culminating the technologies assessment process.

The overall technologies prioritization process used for the Spaceliner 100 Propulsion Technologies Prioritization Workshop was based directly on the Analytic Hierarchy Process (AHP) methods and techniques developed by SAIC for the Advanced Space Transportation Program beginning in the Fall of 1997. The AHP methodology is based on defining a hierarchy of prioritization criteria, collaboratively weighting the criteria, and then collaboratively making pairwise comparisons of the candidate technologies against each of the evaluation criteria. The pairwise comparisons are recorded according to an established numerical scale, and may be based on either quantitative or qualitative information. The resulting collaborative input data are processed to produce a numerical prioritization of the candidate technologies. The collaborative process was successfully tested by an inter-Center NASA team of 16 evaluators at an experimental workshop held at the Langley Research Center in 1998. Twenty candidate advanced technologies were prioritized based on their potential to enable the development of a particular wing-body configuration of a second generation reusable launch vehicle (RLV) system.

The collaborative process was further evolved along with a facilitation software tool and applied by the SPST to prioritize candidate in-space propulsion technologies for applications to five robotic space mission categories, at a workshop conducted at SAIC facilities in McLean, Virginia during April 19 - 22, 1999. A total of 44 on-site and off-site personnel from across NASA, industry and the DoD participated.

In September 1999, a series of four technology prioritization workshops was facilitated by SAIC in the MSFC Collaborative Engineering Center (CEC) for second generation RLV applications in support of the Phase III Space Transportation Architecture Studies. Workshops were conducted for clean sheet and Shuttle-derived RLV applications, and for generic subsystem-level technologies across all disciplines.

The SPST Spaceliner 100 prioritization workshop was conducted over a two and one-half day period, April 5 - 7, 2000, in the NASA MSFC Collaborative Engineering Center.

At the workshop, the evaluators were given an update on the candidate technologies to be prioritized and a briefing to discuss the evaluation criteria and their interpretation.

There were a total of approximately 50 people who participated in the workshop either as evaluators, observers, SPST representatives, on-site or off-site technology advocates/ presenters, or facilitators.

2.0 Product

The 23 technologies were prioritized at the workshop in three ways: based on technical criteria, based on programmatic criteria, and based on a combination of both criteria. The results were presented to NASA/MSFC/ASTP for use in their technology planning process.

The technologies were independently prioritized in the three categories of "Enabling/Generic Technologies", "Flight Systems", and "Ground Systems". They are presented below, as prioritized at the workshop, in the three categories. The name and affiliation of the author responsible for gathering each technology is also included.

2.1 Enabling/Generic Technologies

1. Long life, light weight propulsion materials and structures (Dan Levack/Boeing-Rocketdyne)
2. Propulsion IVHM (June Zakrajsek/GRC)
3. Advanced cryotank structures (Earl Pansano/Lockheed Martin)
4. Combined OMS/RCS (Dan Levack/Boeing-Rocketdyne)
5. Numerical propulsion system simulations (NPSS) for space transportation propulsion (Karl Owen/GRC)
6. Green, operable RCS (Eric Hurlbert/Primex and Stacy Christofferson/Primex)
7. Aerodynamic performance and control through drag modulation (Ray Chase/ANSER)
8. High performance hydrocarbon fuels (Joe Ciminski)
9. Thrust augmentation (Mike Blair/Thiokol)
10. High (better than densified density hydrogen) (Bryon Palaszewshe/GRC)
11. Bridge to space (tether second stage) (Tom Mottinger/Lockheed Martin)

2.2 Flight Systems

1. Long life, high T/W hydrogen rocket (Dan Levack/Boeing-Rocketdyne)
2. SSTO hydrogen RBCC (Dick Johnson/Aerojet)
3. TSTO hydrogen airbreather (Bill Escher/SAIC)
4. Long life, high T/W hydrocarbon rocket (Uwe Hueter/MSFC)
5. Pulsed detonation engine rocket (Dan Levack/Boeing-Rocketdyne)
6. Airbreathing pulsed detonation engine combined cycle (Dan Levack/Boeing-Rocketdyne)
7. SSTO TBCC airbreather (Bill Escher/SAIC)
8. Hydrocarbon TSTO RBCC (Dick Johnson/Aerojet)

2.3 Ground Systems

1. Intelligent instrumentation and inspection systems (Edgar Zapata/KSC)
2. Advanced checkout and control systems (Edgar Zapata/KSC)
3. Advanced umbilicals (Edgar Zapata/KSC)
4. On-site, on-demand production and transfer of cryogenics (Edgar Zapata/KSC)

A much more extensive report of the effort is available as a reference "Report of SPST Support of Spaceliner 100 Technologies Planning", The Space Propulsion Synergy Team, for The Advanced Space Transportation Program, NASA, Marshall Space Flight Center, May 24, 2000.

Appendix IV

1.0 Results of Bottom-Up Team Prioritization

SPST Propulsion Technologies Prioritization to reduce costs and increase safety:

1. Automated predictive maintenance
2. Critical failure identification
3. Systems health verification
4. MPS low thrust mode for OMS
5. Preflight checklist
6. Integrated RCS/OMS
7. Integrated Propulsion/Thermal/Power
8. Integrated RCS/OMS/PPS
9. Elimination of support systems
10. Active TPS elimination
11. Elimination of Turnaround operations
12. Leak free joints
13 Active thermal control elimination
14. Air breathing main propulsion
15. High performance subsystems
16. Single main propellant
17. Simplified mating operations
18 Pyrotechnics elimination
19. All rocket cycle
20. Lightweigh subsystems
21. System failure tolerance
22. Cleaning alternatives
23. Passive aerodynamic solutions
24. Wireless communication
25. Cryogenic conditioning
    25.1 Liquid Hydrogen
    25.2 Liquid Helium
    25.3 Liquid Oxygen
    25.4 Liquid Nitrogen
    25.5 Liquid Methane
26. Residual gases utilization

The highest priorities with the largest leverage are the following technologies:

- Reduce the number of subsystems to be developed
- Increase system margins
- Simply thermal control of flight vehicle

The results of the team's extra assessments of technology areas for their potential to increase safety and reduce costs are:

- IVHMS technologies—automated predictive maintenance and system health verification
- Operations technologies with a high potential for cost reductions are:
  - Elimination of turnaround operations
  - Elimination of support systems
  - Simplified mating operations
  - Use of single propellant

Reference: SPST Presentation to MSFC March 4, 2002 titled "SPST Integrated Technology Team (Bottom-up Team)" by Jay Penn and Pat Odom.

Appendix V

Shuttle Reference Case 1: safety driven functional requirements

- Number of safety driven functional requirements to maintain safe control of systems during flight and ground operations:
    - ET element:
        - Nose cone inerting heated GN2 purge
        - Intertank inerting heated GN2 purge
        - GH2 ground umbilical plate He purge
        - Hazardous gas detection system in the intertank
        - Hazardous gas detection (GH2 sensors) for GH2 ground umbilical plate interface
        - Lox anti-geysering He bubbling system
    - Orbiter – MPS
        - Lox POGO suppression system
        - Aft compartment GN2 purge
        - Aft compartment hazardous gas detection system
        - Orbiter/ET Lox umbilical He purge
        - Orbiter/ET LH2 umbilical He purge
        - Orbiter/ET LH2 umbilical hazardous gas detection system (GH2 sensors)
        - Orbiter/Ground Lox umbilical He purge
        - Orbiter/Ground LH2 umbilical He purge
        - Orbiter/Ground umbilical hazardous gas detection system (GH2 sensors)
        - LH2 main feedline manifold high point bleed system
    - SSMEs
        - LH2 turbopump thermal conditioning system (3)
        - Lox turbopump thermal conditioning bleed system (3)
        - Lox turbopump seal He purge system (3)
        - GH2 lead flow burn-off ignition system (6)
        - SSME/MLP exhaust sound suppression system
        - MLP deck sound suppression system from SSME driven drift at liftoff
    - Orbiter OMS/RCS
        - FRCS compartment GN2 purge
        - APS right side pod compartment GN2 purge
        - APS left side pod compartment GN2 purge
        - FRCS fuel umbilical system purge
        - FRCS ox umbilical system purge
        - APS right side fuel system umbilical purge for OMS
        - APS right side ox system umbilical purge for OMS
        - APS right side fuel system umbilical purge for RCS
        - APS right side ox system umbilical purge for RCS
        - APS left side fuel system umbilical purge for OMS
        - APS left side ox system umbilical purge for OMS
        - APS left side fuel system umbilical purge for RCS
        - APS left side ox system umbilical purge for RCS

    - Operational personnel SCAPE suit system (plus maintenance systems for support)
    - Toxic vapor detection system (many sensors & personnel badges @ 3 stations)
    - Hazardous waste management systems (used @ 3 major stations–OPF,HMF, & Pad
- Orbiter PRSD
    - LH_2 & GH_2 umbilical plate He purge system (several and dependent of # of tanks)
    - Lox & Gox umbilical plate purge system (several and dependent of # of tanks)
- SRB’s
    - Aft skirt GN_2 purge (2)
    - Field joint heater system (10)
    - Ignition overpressure suppression & control system (one foot H_2O coverage of top of exhaust opening) (2)
    - Ignition overpressure suppression & control H_2O injection of MLP exhaust (2)

Appendix VI

Shuttle Reference Case 2 for safety driven limited access control

- Number of safety driven limited access control operations:
  - Orbiter aft compartment
  - ET Intertank
  - SRB aft skirt (2)
  - Handling SRB segments (8)
  - Lifting and handling the Orbiter
  - Lifting and handling the ET
  - Installing and connecting ordnance in system (~200 in orbiter)
  - Installing and connecting ordnance in SRB (~12)
  - Installing/mating booster separation motors on Shuttle
  - Installing and connecting ordnance on separation motors
  - Servicing APU's with hydrazine on Orbiter (3)
  - Servicing APU's with hydrazine on SRB's (4)
  - Propellant servicing OMS & RCS on Orbiter (3 locations @ PAD, 3 locations @ OPF, & HMF)
  - Performing any maintenance on Orbiter OMS, RCS & APU's at OPF & HMF (3 stations)
  - Performing any maintenance on hypergolic systems and re-supply of propellants at PAD (7)
  - Performing recovery & recycle on SRB APU's (2 stations)
  - Servicing Orbiter NH3 & Freon 21 systems (5)
  - Loading cryogenic propellant on the integrated Shuttle Orbiter/ET @ the pad (2)
  - Replenishing the cryogenic (LH2 & Lox) propellant at the Pad storage tanks (4)
  - Loading/servicing the Orbiter Fuel cell/PRSD cryogenic system at the PAD (Lox & LH2)
  - Preparing high purity Lox for the Orbiter fuel cell/PRSD system

Appendix VII

Operability TPM Development/Selection Process

Functional Attributes Desired of the Current System: "WHAT'S" DESIRED

1. Affordable / Low Life Cycle Cost	**2. Very Dependable System**
1.1 Low Recurring cost	2.1 Highly Reliable Hardware
1.2 Low Vehicle/Sys Replacement Cost	2.2 High Intact Vehicle Recovery Rate
1.3 Low Sensitivity to Flt Growth Cost	2.3 High Mission Success Rate
1.4 Low Direct and Indirect Labor Cost	2.4 Very Robust
1.5 Min Payload Cost Impact on Launch Sys	2.5 Always Operates on Command
1.6 Must Close Commercial Bus Case	2.6 High Design Certainty
3. Highly Responsive to Space Customer's Needs	**4. Safety of Hardware and Personnel Very High**
3.1 Very Flexible to Destination Locations & Manifesting (Capable of surge/launch on demand)	4.1 Flight & Ground Hardware safety derived from highly reliable & maintainable parts/systems
3.2 Responsive to Desired Capacity Range	4.2 Public & Personnel Safety derived from Very Reliable/Maintainable Flight & Ground Systems
3.3 Minimum and Ease of Process Verification	4.3 Environmental Safety/Compatibility with Space, Atmosphere, and Ground
3.4 Designed in Automatic Functional Health Verification	5. **Low Acquisition Risk Compatible with Investor's Incentive**
3.5 Designed in and Automatic System Corrective Action	5.1 Technology Maturity Very High for ALL Systems
3.6 Vehicle/ Payload/Ground Integration Ease	5.2 Acquisition Cost Well Understood and Compatible with Commercial Business Case Closure
3.7 Maintainable (minimum and very accessible maintenance)	5.3 Technology Options Available and Mature at Acquisition Start (No open R&D required existing)
3.8 Labor Skills Required to Operate Low	5.4 Acquisition Schedule Compatible with Commercial Business Case
3.9 Easily Supportable (minimum support infrastructure required)	

<u>“HOW’S” TECHNICAL PERFORMANCE METRICS (TPMS)</u>

Matrix for SL 100 Transportation Propulsion Design Criteria Weighting (Operational Phase)

SORT

(Quality Characteristic) Benefit Criteria		Ave. Isp on refer. trajectory (+)	# new unique approaches (+)	# of toxic fluids (-)	Design Variability (-)	Hours for turnaround (between launches or commit to new mission) (-)	Mass Fraction required (-)	#pollutive or toxic materials (-)	Amount of energy release from unplanned reaction of propellant (-)	# of engine restarts required (-)	Transportation trip time (-)	# of components with demonstrated high reliability (+)
(Demanded Quality)	**List Number**	###	###	###	87	88	89	1	2	74	85	86
ATTRIBUTES	**WEIGHT**											
Affordable / Low Life Cycle Cost												
Min. Cost Impact of Payload on Launch Sys.	2.431	9	0	3	1	1	9	1	1	1	9	9
Low Recurring Cost												
Low Cost Sens. to Flt. Growth*	1.62	3	0	3	0	9	3	3	1	0	9	1
Operation and Support	7.60	9	0	9	3	9	9	9	9	1	9	9
Initial Acquisition	0.00	3	0	9	9	3	9	3	1	1	0	3
Vehicle/System Replacement	2.74	3	0	3	1	3	3	0	0	1	0	1
Dependable												
Highly Reliable	3.798	3	0	3	9	0	3	3	1	3	3	9
Intact Vehicle Recovery	2.53	3	0	1	3	0	3	0	3	9	0	3
Mission Success	0.68	1	0	3	9	1	3	1	3	9	9	9
Operate on Command	7.60	0	0	9	3	9	3	3	1	0	1	9
Robustness	3.80	3	0	1	9	0	9	0	0	3	1	3
Design Certainty	3.80	9	0	0	9	0	9	0	0	3	3	9
Responsive												
Flexible	1.22	3	0	1	1	1	3	1	0	0	3	1

Affordable/Low Life Cycle Cost

PRIORITY SELECTION PROCESS

Operation and Support			
	Correlation Value	Raw Score	Benefit Criteria
	9	633.744	# of active systems required to maintain a safe vehicle (-)
	9	600.679	# of different propulsion systems (-)
	9	588.672	# of systems with BIT BITE (+)
	9	579.799	# of components with demonstrated high reliability (+)
	9	574.569	# of hands on activities req'd (-)
	9	566.944	# of active components required to function including flight operations (-)
	9	566.284	# of potential leakage / connection sources (-)
	9	559.8	# of systems requiring monitoring due to hazards (-)
	9	533.855	System margin (+)
	9	523.846	% of propulsion system automated (+)
	9	512.347	# of toxic fluids (-)
	9	506.522	% of propulsion subsystems monitored to change from hazard to safe (+)
	9	499.832	# of unique stages (flight and ground) (-)
	9	498.679	# of in-space support sys. req'd for propulsion sys. (-)
	9	491.89	# of active on-board space sys. req'd for propulsion (-)
	9	489.86	On-board Propellant Storage & Management Difficulty in Space (-)
	9	460.076	# of purges required (flight and ground) (-)
	9	453.799	# of confined spaces on vehicles (-)
	9	446.222	# of active ground or in-space systems required for servicing (-)
	9	440.765	# of checkouts required (-)
	9	438.656	Technology readiness levels (+)
	9	435.823	# of different fluids in system (-)
	9	421.874	# of inspection points (-)
	9	383.499	ISP Propellant transfer operation difficulty (resupply) (-)
	9	381.741	Hours for turnaround (between launches or commit to new mission) (-)
	9	379.602	Mass Fraction required (-)
	9	374.19	# of expendables (fluid, parts, software) (-)
	9	369.733	#pollutive or toxic materials (-)
	9	322.371	# of element to element interfaces requiring engineering control (-)
	9	301.213	# of umbs. req'd to Launch Vehicle (-)
	9	282.954	# of physically difficult to access areas (-)

Vehicle/System Replacement			
	Correlation Value	Raw Score	Benefit Criteria
	9	600.679	# of different propulsion systems (-)
	9	335.896	Minimum Impulse bit (-)
	9	300.856	# of parts (different, backup, complex) (-)
	9	262.873	Integral structure with propulsion sys. (+)
	9	155.118	lbs. Intg.wet & dry mass of propulsion sys. (-)
	9	102.605	# of hazardous processes (-)
	9	87.006	# of processing steps to manufacture (-)
	9	40.419	Hardware cost (-)
	3	633.744	# of active systems required to maintain a safe vehicle (-)
	3	566.944	# of active components required to function including flight operations (-)
	3	512.347	# of toxic fluids (-)
	3	499.832	# of unique stages (flight and ground) (-)
	3	498.679	# of in-space support sys. req'd for propulsion sys. (-)
	3	491.89	# of active on-board space sys. req'd for propulsion (-)
	3	489.86	On-board Propellant Storage & Management Difficulty in Space (-)
	3	446.222	# of active ground or in-space systems required for servicing (-)
	3	435.823	# of different fluids in system (-)
	3	427.162	# of propulsion sub-systems with fault tolerance (+)
	3	381.741	Hours for turnaround (between launches or commit to new mission) (-)

Appendix VIII

Glossary:

List of Acronyms

AHP	Analytic Hierarchy Process
APS	Auxiliary Propulsion System
APU	Auxiliary Power Unit
ASTP	Advanced Space Transportation Program
CEC	Collaborative Engineering Center
CG	Center of Gravity
Crit	Criticality
DDT&E	Design, Development, Test and Evaluation
Delta V	Velocity change
ELV	Earth Launch Vehicle
ESMD	Exploration Systems Missions Directorate
ET	External Tank
ETO	Earth-To-Orbit
FRCS	Forward Reaction Control System
Gen 3	Third Generation
GH2	Gaseous Hydrogen
GOX	Gaseous Oxygen
GRC	Glenn Research Center
GSE	Ground Support Equipment
HMF	Hypergolic Maintenance Facility

H2O	Water
ISS	International Space Station
IVHM	Integrated Vehicle Health Monitoring
JSC	Johnson Space Center
KSC	Kennedy Space Center
LCC	Life Cycle Cost
LEO	Low Earth Orbit
LH2	Liquid Hydrogen
MECO	Main Engine(s) Cutoff
MLP	Mobile Launch Platform
MPS	Main Propulsion System
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NH3	Ammonia
NHB	NASA Handbook
NPC	Non-Propulsive Consumables
NSTS	National Space Transportation System
ODS	Orbiter Docking System
OMS	Orbital Maneuver System
PAD	Program Approval Document
PL	Payload
POGO	launch vehicle induced oscillations (not an acronym; derived from "pogo stick" analogy)

PPS	Power Processing System
PRSD	Power Reactants Storage and Distribution
RBCC	Rocket Based Combined Cycle
RCS	Reaction Control System
R&D	Research and Development
SAIC	Science Applications International Corporation
SBS	Systems Breakdown Structure
SCAPE	Self-Contained Atmospheric Protective Ensemble
SE&I	Systems Engineering and Integration
SLWT	Super Lightweight Tank
SPST	Space Propulsion Synergy Team
SRB	Solid Rocket Booster
SRM	Solid Rocket Motor
SBS	Systems Breakdown Structure
SSME	Space Shuttle Main Engine
SSTO	Single Stage To Orbit
TBCC	Turbine Based Combined Cycle
TBD	To Be Determined
TPM	Technical Performance Measure
TPS	Thermal Protection System
TRL	Technology Readiness Level
TSTO	Two Stages To Orbit
TV	Television

TVC	Thrust Vector Control
VAB	Vertical Assembly Building
VAFB	Vandenburg Air Force Base
WBS	Work Breakdown Structure