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Report of

Current Space Shuttle System Shortfalls Assessment

Produced by

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

For the:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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Director Strategic Investments

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Current Space Shuttle System "Shortfalls Assessment"

Table of Contents

Current Space Shuttle System “Shortfalls Assessment”

Executive Summary

Recommendations. It is clear from the “Shortfall Assessment” performed by the national space propulsion synergy team (SPST) and summarized in this document, that past and current Shuttle Program efforts to control life cycle costs (LCC) have been inadequate and ineffective. Therefore, the (SPST) is recommending NASA consider adopting the proven methods of controlling weight and performance and applying them to controlling cost (LCC). It is also recommended that the NASA consider using the SPST technique for balancing Safety, Reliability, and Maintainability requirements to provide controls on recurring maintenance burden to provide operational effectiveness and LCC. In addition, the future programs need a complete functional systems breakdown structure (Functional SBS) of all activities to provide the total visibility of the entire task. This functional SBS will allow the systems engineering activities to totally integrate each discipline to the maximum extent possible and optimize at the total system level. Optimizing at the individual sub-system level creates a very large support infrastructure (very large labor workforce) associated with resultant high LCC.

The SPST recommends that the Program Analysis and Evaluation Office endorse these SPST recommendations and implement requirements for all new NASA programs to require these LCC and operational controls. Further the SPST recommends that these new approaches be implemented immediately 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. In addition, this effort will help re-gain NASA’s cost creditability with the country’s leaders.

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 and any future systems 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. It is also learned that NASA must balance the Safety, Reliability, and Maintainability requirements to provide controls on recurring maintenance burden to provide operational effectiveness and LCC.

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 but not controlled).

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 the current space transportation system shortfalls assessment and supporting analyses that have been conducted by the Space Propulsion Synergy Team (SPST). These studies directly address the "lessons learned" from previous transportation systems and the way NASA does business, as well as recommended/suggested solutions for improvement. The SPST has 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. 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 DDT&E 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 – total program optimization.

Insight gained from performing the shortfalls assessment stresses the need to perform optimization at the total systems level and not at the sub-system level (stove-piping). The SPST has 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 briefly 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 developed 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. This SPST report is available under separate cover.

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 stimulating 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 and the chief systems engineer. This effort is not included in this report, but is available on the SPST web site at the NASA MSFC Virtual Research Center at Huntsville (VRC).

1.0 Introduction

In the spring of 2002, Dan Dumbacher, the Second Generation Reusable Launch Vehicle (2GRLV) Deputy Program Manager, requested that the SPST review and critique the 2GRLV Program Level I Requirements documents. He specifically was interested in a critique of these requirements regarding their capability of assuring the design, development and eventually the operation of a Space Transportation service that would meet the 2 GRLV Program goals/objectives. It was stated in the 2GRLV Requirements document that the 2GRLV Level I architecture requirements are derived from an understanding of NASA, commercial, and projected DOD mission needs, and from identified areas for improvement gleaned from experience with the existing fleet of launch vehicles. The 2GRLV program personnel, working to a short schedule chose to by-pass the assessment of existing launch vehicles for shortfalls and to identify the needs for improvement. After some time, the SPST Requirements Sub-team agreeing this was an important step in the identifying of requirements for a next generation space launch system, undertook this task. Being a mostly volunteer task, it has been aborted several times for higher priority work and is just now being formally completed.

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 NASA has 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. The 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.

This report describes the development of the process used to document the current space transportation system shortfalls providing a clear visibility for the need to improve on both the technical and management processes required to achieve the objectives desired of a next generation space transportation system.

Current Space Shuttle System “Shortfalls Assessment”

The basic approach by SPST to the task of providing defining and documenting the current system shortfalls is to compare the achievements to the original requirements, objectives, and goals of the system being provided. This includes technology, advanced development, DDT&E, Manufacture, Operational, and Recycle/Disposal phases of the current program.

The SPST proposes to address the global problem of ignoring past program lessons learned, technical issues that get passed from one program to the next, and not taking these shortfalls into consideration in developing the architectural concept along with its requirements formulation by providing this formal report to the responsible decision maker at the start of the major undertaking of providing a replacement space transportation system.

2.0 The SPST Approach

The objective of the study was to define the major program shortfalls for the Space Shuttle Transportation System both programmatic and technical. The approach was to define and document the major program requirements/objectives/goals at the first and second levels. The next step was to define and document the accomplishments to each of the requirements/objectives/goals documented. The shortfalls were then documented along with need statements for improvement to the next generation Space Transportation System. This data was analyzed to determine the cause for the shortfall so that the appropriate corrective action could be identified. This effort could be stated as the lessons learned from the Space Shuttle program.

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 has many requirement, objective, and goals shortfalls. By looking at its history, the SPST determined 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 and are presented in this report.

3.1.1 Space Shuttle Level 1 Program Requirements Document

Space Shuttle Program Level 1 documentation excerpts of interest can be found in Appendix I. This copy is the last revision maintained in original context before revising to show conformance to achievement. This document will also serve as the primary Requirements, Objectives, and Goals reference for this shortfalls analysis.

3.1.2 Space Shuttle History Overview

A historical perspective of many of the shuttle program operations parameters were established to provide visibility and allow insight to shortfalls in the program. This shuttle operations perspective matrix can be found in Appendix II.

3.1.3 Space Shuttle Fluids Overview

Insight into one of the operational characteristics (number of different fluids required) was gained by building a matrix of all the fluids used by the Shuttle launch vehicle and providing visibility to their sub-systems use and its cleanliness requirements. This information shows there are 102 total unique sub-systems that require fluid servicing for each launch and several using the same commodity (17 separate He servicing locations). This assessment indicates a total lack of integration of flight functions to require the minimum ground infrastructure, flight hardware logistics support, and minimum sustaining engineering. Composite matrix can be found in Appendix III.

3.1.4 Hardware Dependability Influence on Propellant Cost/LCC Goals

This analysis provides insight that the depot maintenance function drives the propellant cost for Shuttle to exceed the flight operations propellant costs. It also indicates that the design life and reliability relationship was not sufficient to meet the expected dependability goals; therefore, driving up the LCC or cost per flight expectations beyond its goal. The insight provided here is that the safety, reliability and maintainability requirements must be balanced to provide controls of recurring cost. Shuttle experience indicated that the recurring cost was left to chance because the maintenance burden (depot cycle) was not controlled by a flow down of requirements. This complete analysis can be found in Appendix IV.

4.0 Space Shuttle Shortfalls and Future STS Needs Overview

NASA Mission and Space Transportation’s Role

NASA’s Vision:

- *To improve life here*
- *To extend life to there*
- *To find life beyond*

NASA’s Mission:

- *To understand and protect our home planet*
- *To explore the Universe and search for life*
- *To inspire the next generation of explorers*

.....As only NASA can

Today, NASA utilizes both the Space Shuttle and expendable launch vehicle transportation systems in accomplishing its mission. Assessments of future needs indicate capabilities of current space transportation systems are not adequate and additional capabilities will be required to accomplish NASA’s mission in the near, mid and far term. Current space activities are constrained by a lack of operational flexibility and responsiveness, high cost, limited in-space maneuver capability, *concerns for safety and reliability, and significant constraints on payload mass and volume.*

Current RLV Space Transportation Systems Shortfalls Identification

In order to identify the requirements needed to develop the systems and the supporting technology for future space transportation systems (near, mid, and far), first the shortfalls must be identified with the current systems. The shortfalls must be identified and analyzed to determine the entire root causes responsible. These shortfalls' root causes must be corrected by developing the needs statements required to identify the global requirements for future space transportation systems. These top level requirements must be followed by the development of the next level requirements that are required to be in place to influence the architectural concepts that will satisfy and correct all the shortfalls of the current systems.

In identifying the shortfalls of current systems all of the desired functional attributes of the space transportation system should be addressed. These functional attributes desired of these systems are listed below.

Functional Attributes Desired of the Current System:

1. Affordable / Low Life Cycle Cost	**2. Very Dependable System**
1.1 Low initial acquisition cost	2.1 Highly Reliable Hardware
1.2 Low Recurring cost	*2.2* High Intact Vehicle Recovery Rate
1.3 Low Vehicle/Sys Replacement Cost	2.3 High Mission Success Rate
1.4 Low Sensitivity to Flt Growth Cost	2.4 Very Robust
1.5 Low Direct and Indirect Labor Cost	2.5 Always Operates on Command
1.6 Min Payload Cost Impact on Launch Sys	2.6 High Design Certainty
1.7 Must Close Commercial Bus Case	
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 and 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)	

Current Space Shuttle System "Shortfalls Assessment"

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 Sub-team 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 Appendix I. The attribute ID column in the table is a reference back to the previous table of attributes by function and their number, e.g., A 1.2 would refer to the Affordable attribute and item "1.2 Low Recurring Cost".

Current Space Shuttle System "Shortfalls Assessment"

4.1 Space Shuttle Shortfalls

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.

Current Space Shuttle System "Shortfalls Assessment"

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:	$100.00/lb to orbit	~ $10,000.00/lb to orbit Actual Shuttle recurring cost over the total 21 operating years = ~ $57.876 Billion.	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.
	All processes and operations must be compatible with environmental regulations and laws	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.	Stringent Environmental /OSHA requirements have been imposed since Shuttle ATP	STS Program didn't include cost allowances for changes in the environmental laws.

Current Space Shuttle System "Shortfalls Assessment"

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.

Current Space Shuttle System "Shortfalls Assessment"

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:	10 flights/yr.	2.5-3 flights/yr.	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.
	Fleet flight rate:	40 flights/yr. at ETR	10 flights/yr.	
	Vehicle turnaround time:	160 hours	1296 hours Min.	
	System performance to LEO	65,000 lbs at ETR @ 28.8 degrees and 100 nmi	55,000 lbs at ETR @ 28.8 degrees and 100 nmi	
	Materials, fluids, and design properties and limitations well understood through failure with narrow tolerances	Considered as over constraining and would have driven up the DDT&E cost considerably.	Because the limits were not known, operational controls provided margins to avoid unplanned events. Performance carried an extra margin to allow for these uncertainties.	

Current Space Shuttle System "Shortfalls Assessment"

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.

Current Space Shuttle System "Shortfalls Assessment"

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.

Current Space Shuttle System “Shortfalls Assessment”

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 contribute to the large resultant cost per flight and the low flight rate.

Current Space Shuttle System “Shortfalls Assessment”

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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.

Current Space Shuttle System "Shortfalls Assessment"

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.

Current Space Shuttle System "Shortfalls Assessment"

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). <u>Note:</u> The orbiter element has ten (10) more facility station ICD's at the launch site.	

Current Space Shuttle System "Shortfalls Assessment"

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.

Current Space Shuttle System "Shortfalls Assessment"

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.

4.2 Future STS Needs

The pursued US Exploration Program 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, 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) or control needs that would help assure a sustainable operational space transportation system architecture. The following section summarizes these TPMs.

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

The following are a recommended listing of "Design for Operability" requirements TPMs control needs. 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 this shortfalls analysis performed on the Shuttle program and reflect the major lessons learned.

It is suggested that a listing of those focus-area measurable criteria that require an Engineering Management structured process be 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 number of separate stages: **Metric Value:** TBD
   Shuttle Reference Value: Many systems in MPS, OMS, RCS, TVC, Thermal Management Systems and Life Support Systems

2. Total number of flight tanks in the architecture: **Metric Value:** TBD
   Shuttle Reference Value: In excess of 95

3. Number of safety driven functional requirements to maintain safe control of systems during flight and ground operations: **Metric Value:** TBD

Shuttle Reference Value: In excess of 70

4. Number of maintenance actions unplanned between missions: **Metric Value:** TBD
   Shuttle Reference Value: ~ 800

5. Number of maintenance actions planned between missions: **Metric: Value** TBD
   Shuttle Reference Value: ~ 2200

6. Total number of traditional ground interface functions required: **Metric Value:** TBD
   Shuttle Reference Value: Hundreds

7. Percent (%) of all systems automated: **Metric Value:** TBD
   Shuttle Reference Value: (Inspections and checkout mostly manual)

8. Number of different fluids required: **Metric Value:** TBD
   Shuttle Reference Value: 24 every flight

9. Total number of vehicle element to element support systems (Major element interfaces such as Orbiter to SSME or ET): **Metric Value:** TBD
   Shuttle Reference Value: Example is the SSME with 26 support systems from the Orbiter (target value should be 12 or less)

10. Number of flight vehicle servicing interfaces: **Metric Value:** TBD
    Shuttle Reference Value: ~102

11. Number of confined/closed compartments: **Metric Value:** TBD
    Shuttle Reference Value: 13 or more

12. Number of commodities used that require medical support operations and routine training: **Metric Value:** 0 Toxics & TBD Special Training
    Shuttle Reference Value: 3 major & 3 minor toxic fluids

13. Number of safety driven limited access control operations: **Metric Value:** TBD
    Shuttle Reference Value: In excess of 266 functions

14. Number of safing operations at landing: **Metric Value:** TBD
    Shuttle Reference Value: TBD

15. Number of mechanical element mating operations (element to element & element to ground): **Metric Value:** TBD
    Shuttle Reference Value: Example: 24 component mating between the one SSME and the Orbiter (A total of 72 total SSME mechanical connections to the Orbiter) Target for a single engine to stage should be more like 9 to 11.

16. Number of separate electrical supply interfaces: **Metric Value:** TBD
    Shuttle Reference Value: Example: 12 electrical components matings needed for each SSME to the Orbiter (A total of 36 total SSME electrical connections to the Orbiter) Target for a single engine to stage should be 4 or less.

17. Number of intrusive data gathering devices: **Metric Value:** TBD
    Shuttle Reference Value: Example : 45 intrusive sensors on each SSME

18. Number of Criticality – 1 (Crit-1) system and failure analysis modes: **Metric Value:** TBD
    Shuttle Reference Value: Example is that there are 550 Crit 1 & 1R failure modes on each SSME

Reference cases 1 and 2 of data for the Shuttle in enclosed as Appendices V and VI.

4.3 Fluid & Propulsion System Technical Generic Needs for Future STS (flight & ground systems)

The Fluid & Propulsion System Technologies Focused Needs for Future Flight and Ground Space Transportation Systems are determined by the desired characteristics focus as follows:

1. Non-intrusive instrumentation
2. Process instrumentation
3. Zero emissions components
4. Elimination of the need for dynamic seals
5. Integrated functions to minimize total number of systems
6. Select passive solutions vs. dynamic components and systems
7. Reduction of total parts count by orders-of-magnitude
8. Increased design life by orders-of-magnitude
9. Increase the Reliability of components and systems by orders-of-magnitude
10. Balance the Maintainability, Safety, and Reliability requirements to produce control of recurring cost by design
11. Produce solutions with orders-of-magnitude less waste
12. Provide smart hardware to provide for health management and control
13. Fully automated systems that result in order-of-magnitude <u>net reductions</u> of personnel requirements

Current Space Shuttle System “Shortfalls Assessment”

4.4 Balancing Safety, Reliability, and Maintainability Requirements

A process and methodology for developing and balancing the quantitative SR&M requirements have been developed at NASA KSC by Tim Adams and Russel Rhodes for the SPST.

The process for developing and balancing quantitative requirements for safety (**S**), reliability (**R)**, and maintainability (**M**) is shown in Figure A. This process derives and integrates Level I requirements and the controls needed to obtain Program key objectives for Safety and Recurring Cost.

The process being quantitative, uses common and standard mathematical models. Even though the process is shown as being worked from the top down, this process can be worked from the bottom up. Figure B provides two illustrations using this process.

This process uses three math models. Starting at the top, the math models are the Binomial Distribution (greater than or equal to case), reliability for a series system, and the Poisson Distribution (less than or equal to case). The Binomial Distribution is equivalent to the commonly known Exponential Distribution or "constant failure rate" distribution. Either model can be used; the Binomial Distribution was selected for modeling flexibility since it conveniently addresses both the zero fail and failure cases. The failure case is typically used for non-human occupied spacecraft as with missiles.

As the first step of the process, the Systems Engineering Designer begins with three inputs, namely, the desired number of missions the program is planning (**n**), the minimum number of successful missions for duration of the program (**x**), and assurance (**A**) of obtaining **x** or more successes out of the **n** missions. In risk terms, **1 - A** is the probability or risk likelihood of not obtaining **x** or more successes out of **n** number of attempts or not obtaining the desired level of safety and reliability. When these three mentioned inputs are used in the Binomial Distribution, the minimum mission reliability (**Ps**) is calculated. At this point of the process, the Level I Safety requirement has been established.

The second step uses the minimum mission reliability (**Ps**) and an estimate of the number of serial LRU elements (**e**) as inputs into the formula for reliability of a series system to calculate minimum element reliability (**Psi**). Maximum element failure rate (**Pfi)** is equal to **1 - Psi**. Without considering the maintainability burden that has a very large influence on recurring cost, the process at this point has established the Safety and Reliability requirements for the program.

The last step addresses the maintainability parameter, the parameter that provides a control for recurring costs due to maintenance and repair. Similar to program reliability (**A**), program maintainability (**M**) is a probability. The probability **M** is determined by the Poisson Distribution and uses the following inputs: the number of missions (**n**), the number of elements (**N**, where $\mathbf{e \le N}$), the LRU failure rate (**Pfi** or **λ**, where $\boldsymbol{\lambda} \le$ **Pfi**), and the maximum number of LRU repairs (**r**). Technically, **M** is the probability of no more than **r** number of repairs occurring at a particular mission using **e** number of LRU's with an average failure rate of **Pfi** or **λ**. To achieve the desired results in both **M** and the desired **A**, adjustments in **e**, **Pfi**, **N**, and **λ** must be made. These values become the enabling requirements to balance and achieve the desired key objectives of the program.

Current Space Shuttle System "Shortfalls Assessment"

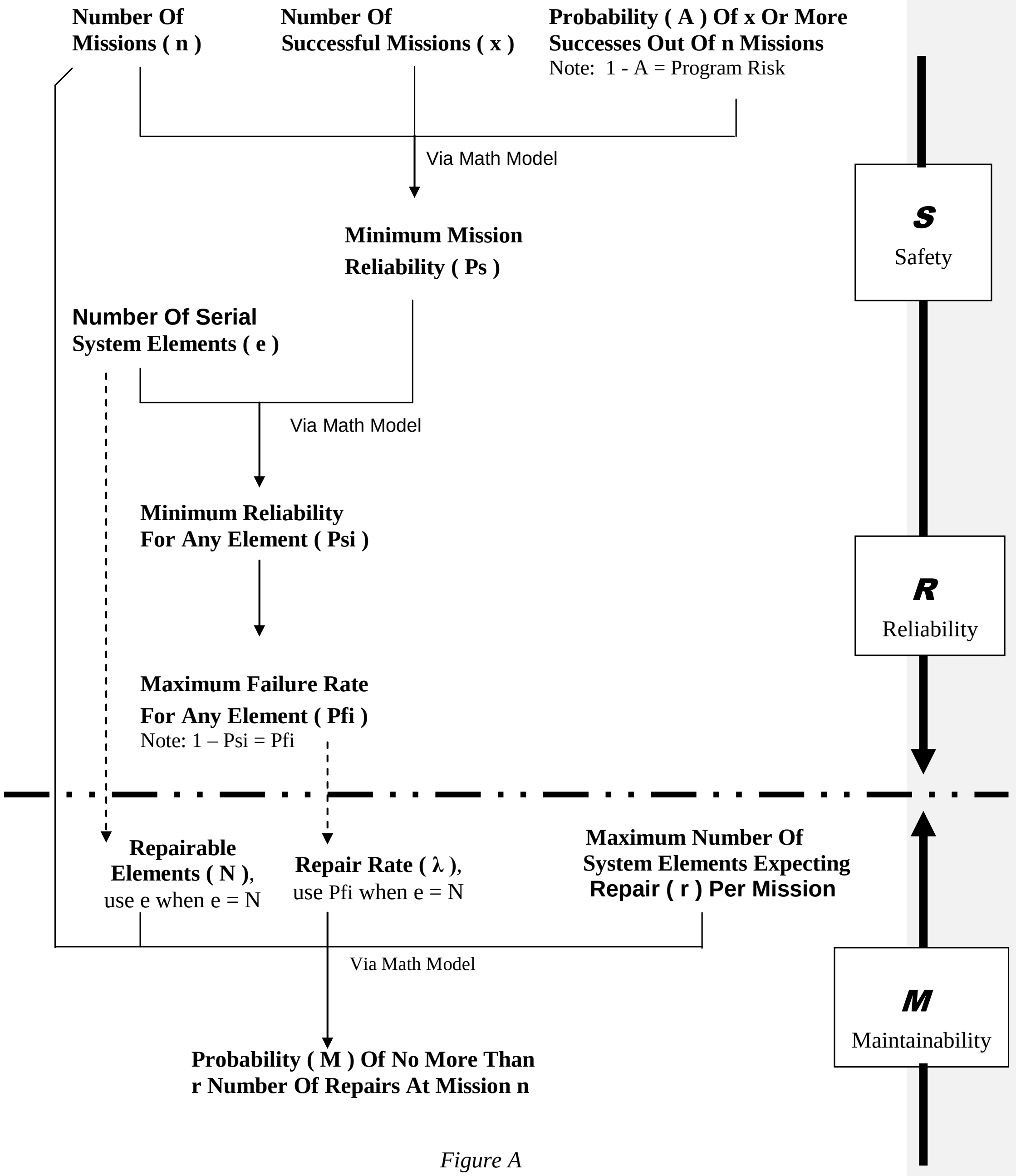

Figure A

<u>S & R Table</u>: Maximum Failure Rate For Each Serial System (Pfi)

		Number of Serial Systems (e)				
		10^{+1}	**10^{+2}**	**10^{+3}**	**10^{+4}**	**10^{+5}**
Assurance (A)*, the probability of 100 successes out of 100	**.90**	1.0535 x 10^{-4}	1.0536 x 10^{-5}	1.0536 x 10^{-6}	1.0536 x 10^{-7}	1.0536 x 10^{-8}
	.95	5.1292 x 10^{-5}	5.1293 x 10^{-6}	5.1293 x 10^{-7}	5.1293 x 10^{-8}	5.1293 x 10^{-9}
	.99	1.0050 x 10^{-5}	1.0050 x 10^{-6}	1.0050 x 10^{-7}	1.0050 x 10^{-8}	1.0050 x 10^{-9}
	.999	1.0005 x 10^{-6}	1.0005 x 10^{-7}	1.0005 x 10^{-8}	1.0005 x 10^{-9}	1.0005 x 10^{-10}

Note: * Assurance (A) is a composite of safety (S) and reliability (R).

<u>M Table</u>: The Probability (M) Of No More Than 1 Element Repair Per Mission

		Number Of Subsystem Elements (N) At The Repair/Maintenance Level**				
		10^{+2}	**10^{+3}**	**10^{+4}**	**10^{+5}**	**10^{+6}**
Maximum Repair Rate For Each Element (λ)	**10^{-3}**	0.9953	0.7356	0.0005	0	0
	10^{-4}	0.99995	0.9953	0.7356	0.0005	0
	10^{-5}	0.9999995	0.99995	0.9953	0.7356	0.0005
	10^{-6}	0.999999995	0.9999995	0.99995	0.9953	0.7356

Note: ** When necessary, count legs in a redundant system as subsystem elements.

<u>Illustration 1</u> (e = N case):

If A = 0.99 for 100 successes out of 100 attempts and e = 100, then Pfi $\approx$ 1 x 10^{-6} will satisfy the **Assurance Requirement**. Since N = e = 100 and Pfi = λ = 1 x 10^{-6}, then the probability of having more than one repair per mission is remote (1 – M = 1 – .999999995 = 5 x 10^{-9}). Thus, the **Maintainability Requirement** at virtually any level will be satisfied.

<u>Illustration 2</u> (e < N case):

If A = 0.99 and e = 100, then Pfi $\approx$ 1 x 10^{-6} will satisfy the **Assurance Requirement**. Assume each of the 100 serial systems contain an average of 1,000 sub-elements, then N = 1,000 x e = 1,000 x 100 = 100,000. Also, assuming each sub-element repair rate is λ = 1 x 10^{-5} and with N = 100,000, then the probability of having no more than one repair per mission is 0.7356 or about 74% -- other words, a 26% chance of 2 or more (up to N) repairs. Thus, the **Maintainability Requirement** at a selected 90% level will not be satisfied.

Figure B

4.5 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 prevent 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.

5.0 Summary

The shuttle shortfalls assessment by the national SPST provides insight into the major areas that needs improvement as well as to the kind of operational criteria that needs to be addressed. This assessment along with other supporting analysis provides a high potential for LCC cost reduction and control by developing and implementing a set of proposed operability design requirements, e.g., technical performance metrics (TPMs). This shuttle shortfalls analysis provides the insight that a structured engineering management process would require 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 is 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.

Current Space Shuttle System "Shortfalls Assessment"

The only shuttle program 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 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 portion of the space transportation LCC is the recurring or operational phase cost.

This space shuttle shortfalls assessment study and its supporting analysis provide a major source of documented knowledge of the shortfalls that developed between initial requirements/objectives and the actual results achieved during the Shuttle Program. 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 developed 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 developed 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 as to why past programs were not 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 desired thrust resulting from this effort is for the NASA 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 the 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. Additionally, the Safety, Reliability, and Maintainability requirements must be balanced to provide the necessary controls on the maintenance burden and frequency of the depot cycle to gain control of process flow time and recurring cost.

It is believed that improved life cycle cost control processes developed by the SPST will provide the necessary cost controls when properly applied in the future to advanced space transportation systems.

7.0 Recommendations

It is clear that past and current efforts to control life cycle costs have been inadequate and ineffective; therefore, the SPST recommends the NASA consider adopting the proven methods of controlling weight and performance and applying them to controlling cost. It is also recommended that the NASA consider using the SPST technique for balancing Safety, Reliability, and Maintainability requirements to provide controls on recurring maintenance burden to provide operational effectiveness and LCC.

The SPST recommends that the Program Analysis and Evaluation Office endorse these SPST recommendations and implement requirements for all new NASA programs to require these LCC and operational controls. Further the SPST recommends that these new approaches be implemented immediately 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 final recommendation is for the SPST Functional Requirements Sub-team to develop an approach to providing LCC controls on major operational cost drivers and provide it to the NASA for their implementation consideration in the Space Exploration Program.

Appendix I
Space Shuttle Level I and II Program Requirements Documentation excerpts

U.S. Gov't

National Aeronautics and Space Administration

SPACE SHUTTLE

PROGRAM REQUIREMENTS DOCUMENT

Revision NO. 8

LEVEL I

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
OFFICE OF SPACE FLIGHT
WASHINGTON, D.C. 20546

June 30, 1977

Current Space Shuttle System “Shortfalls Assessment”

U.S. Gov't

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.

1.2 CHANGES. This document will be controlled in accordance with approved Space Shuttle Program Directive No. 1.

1.3 RELATED DOCUMENTS. This document is in accord with the approved program approval document and program plan. Further detail pertaining to technical and operational requirements and to payload accommodations can be found in Level II documentation.

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.

2.3 PAYLOAD BAY GEOMETRY. The payload bay shall be sized to have a clear volume of 15 ft. (4.5 meters) diameter by 60 ft. (18.2 meters) length. Payloads including their thermal and dynamic deflections shall be contained in an envelope equal to or less than 15 ft. (4.5 meters) in diameter and 60 ft. (18.2 meters) length. Payload attachment fittings and umbilicals shall extend beyond this envelope in order to mate with standard orbiter fittings which are outside the payload envelope. A standard deployment mechanism and tie points shall be chargeable to the Orbiter Vehicle and shall not occupy the clear volume when stowed. Clearance for deployment and Orbiter deflections shall be provided by the Orbiter Vehicle. Available payload volume is reduced when the orbiter Maneuvering System (OMS) incremental Delta V tankage or the docking module is carried.

,U.S. Gov't

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.

2.5 CREW/PASSENGER ACCOMMODATIONS. The cabin shall be designed to accommo0ate a total crew of seven, three crewmen to operate the orbiter and up to four payload specialists. The orbiter shall be provisioned for support of these personnel for 28 man days and up to 42 man days with no system change. All crew systems (such as seats and intercoms) for crew size greater than four and all consumables for duration greater than 28 man days shall be provided in kit form and shall be charged to payload. The design shall not preclude installation of crew support equipment for a total of 10 crew members as would be required to implement an Orbiter-to-Orbiter rescue.

2.6 CABIN ATMOSPHERE. The Orbiter crew and passenger environment shall be a shirt-sleeve, nominal 14.7 psi (760 mm Hg), two gas atmosphere (Nitrogen-Oxygen) to simulate sea level composition.

Comment [leh1]:

2.7 EXTRA VEHICULAR (EVA) PROVISIONS. The orbiter shall provide an airlock, crew provisions and support hardware for crew access to and from the unpressurized payload bay and pressurized modules, for orbiter and payload EVA operations, and for space rescue. The airlock will be capable of being mounted either inside or outside the cabin on the forward bulkhead of the payload bay and will be capable of being used in conjunction with a spacelab tunnel adapter to provide continuous spacelab-to-cabin access during EVA. To support rescue, all Shuttle Flights will carry EVA provisions for two trained crewmen and personnel rescue systems for all other crew members.

[#] 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.

2.9 SPACE SHUTTLE MAIN ENGINES (SSME). The Space Shuttle Main Engines will meet the requirements specified in the approved

*Information changed by Revision 8

[#] For record of Deviation/Waivers granted against this requirement, refer to JSC 07700, Volume X.

Space Shuttle Orbiter Vehicle/Main Engine ICD. Three engines will be used in the orbital flight configuration.

* 2.10 REACTION CONTROL SUBSYSTEM (RCS). An Orbiter RCS shall provide three-axis angular control, including vernier angular control, and three-axis translation capability.

* 2.11 ORBITAL MANEUVER SUBSYSTEM (OMS). The OMS shall provide the propulsive thrust to perform final insertion into orbit, circularization, orbit transfer, rendezvous and deorbit. The OMS tankaqe shall be sized for a Delta V capability of 1,000 ft/sec (305 m/sec) with a 65,000 lb payload. This Delta V capability includes the final orbit injection Delta V from external tank separation to 50 x 100 n. mi. (93 x 185 km) insertion orbit. Provisions shall be made to allow additional tankage to be incorporated in three Delta V increments of 500 ft/sec (152 m/sec) each for an overall total Delta V capability of 2,500 ft/sec (762 m/sec). The additional tankage and propellants will be located id the payload bay and the weights and volumes thereof charged to payload.

2.12 AIRBREATHING ENGINE SUBSYSTEM (ABES). (Deleted).

2.13 SOLID ROCKET BOOSTERS (SRB's). The SRBs will meet the requirements specified in the approved Space Shuttle Orbiter Vehicle/ET/SRB Interface Control Document. The two SRBs will operate in parallel with the main engines to provide impulse to the Orbiter Vehicle from lift-off to staging. the SRBs shall be designed for water recovery, refurbishment and subsequent reuse. As a design objective, the SRB case should be capable of 20 uses.

* 2.14 EXTERNAL TANK (ET). The expendable External Tank will carry hydrogen and oxygen propellant for the main engines. The ET will conform to the requirements of the approved Space Shuttle Orbiter Vehicle/ET Interface Control Document.

2.15 RADIATION AND AVIONICS. (Deleted).

2.16 COMMUNICATIONS SUBSYSTEM. The Orbiter shall be capable of direct voice command, telemetry and video communication with the ground. The Orbiter shall be capable of communication by relay through a communication satellite system. Provisions shall be made to accommodate equipment for secure voice and data communication.

2.17 LANDING SYSTEM. The Orbiter Vehicle shall have an automatic landing system.

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.

*Information changed by Revision 8

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2.19 INTERNATIONAL DOCKING SYSTEM. The Orbiter Vehicle shall meet the international requirements negotiated for compatible rendezvous, docking and crew transfer systems. The docking module will be provided as an optional kit in the payload bay and will be chargeable to payload.

2.20 ELECTROMAGNETIC COMPATIBILITY. The Space Shuttle system, shall be designed and tested in accordance with JSC Specification SL-E-0001. Subsystems and/or individual equipment shall be designed and tested in accordance with JSC specification SL-E0002.

*2.21 RANGE SAFETY FLIGHT TERMINATION SYSTEM. The Shuttle vehicle shall have a range safety flight termination system for Orbital Flight Test Operations involving an Orbiter equipped with ejection seats.

*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

*Information changed by Revision 8

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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,OOC 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.

d. 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).

e. 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.

3.3 LAUNCH AZIMUTH. The Space Shuttle System shall have a variable azimuth launch capability to satisfy the acceptable launch-to-insertion azimuths from both the KSC and Vandenberg AFB launch sites.

3.4 CROSSRANGE. The Orbiter Vehicle shall have the aerodynamic crossrange capability to return to the launch site at the end of one revolution for all inclinations within the Space Shuttle System capability. Crossrange is to be achieved during entry, which is defined as beginning at 400,000 ft (122 km) altitude and ending at 50,000 ft. (15 km) altitude.

3.5 RETURN PAYLOAD. The Orbiter Vehicle shall have the capability to land the design return payload of 32,000 lbs. (14,515 kg) with nominal wind and load factors and up to 65,000 lbs. (29,483 kg) return payloads under increased landing condition constraints.

3.6 LOAD FACTORS. The Space Shuttle System launch trajectory resultant load factors shall not exceed 3 G's for the Orbiter Vehicle. These limits do not apply to abort modes. The product of G forces and time shall not be detrimental to the crew/passengers.

3.7 TURNAROUND. When operational the Space Shuttle System flight hardware turnaround from landing return to the launch facility to launch readiness shall not exceed 160 working hours covering a span of 14 calendar days for any class mission.

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3.8 LAUNCH FROM STANDBY. The Space Shuttle System design shall provide the capability to be launched from a standby status within 2 hours, and hold in a standby status for 24 hours. Standby status is defined as ready for launch except main propellant fill, crew ingress and final systems verification.

Waiver: 1) For KSC launches, the time from standby to launch shall be a 4-hour capability.

2) For VAFB launches, the time from standby to launch shall be four (4) hours. This may be reduced to three (3) hours should parallel crew ingress during MPS loading be permitted and to two (2) hours by further automating the cabin pressure integrity check.

3.9 RESCUE. To fulfill the space rescue role, the Space Shuttle System shall have the capability to launch within 24 hours after the vehicle is mated and ready. for transfer to the pad. if the spacecraft requiring aid has a docking system on that mission, the primary rescue mode will te ry docking, with crew transfer through a pressurized tunnel. Otherwise, emergency rescue will be with pressure suits and personal rescue systems outside the spacecraft. The Orbiter Vehicle shall be capable of supporting the survival of a 4 man crew for 96 hours after an on-orbit contingency. Support for additional personnel shall be provided by the Orbiter and charged to the payload per paragraph 2.5.

Waiver: For KSC launches, the time requirement from Notification to launch shall be 26.5 hours.

3.10 ABORT. The Space Shuttle System shall provide a safe mission termination capability through all mission phases. The performance capability to meet this requirement is defined as follows:

a. Crew and Passenger Ingress Through Launch Commit Phase. The emergency egress shall provide for crew add passenger evacuation to a safe area in a maximum time of two minutes (from crew ingress to swing arm retract).

b. Launch Commit Through Return to Site Capability Phase. The Shuttle System shall have a performance capability of intact (crew, payload and vehicle) abort and return to the launch site. The system design shall include adequate provisions for external tank separation and disposal.

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c. Return-to-Site Through Orbit Insertion Phase. The orbiter shall have the capability (with one main engine out) to abort once around and return to the primary landing site from the point in the flight trajectory where a direct return-to-launch-site capability ends.

d. Orbital and Reentry Phase. The abort mode after orbit insertion shall be early mission termination and return to a suitable landing site.

3.11 LOITER TIME. (Deleted).

3.12 ORBITER TRANSPORT. The Orbital Vehicle shall be capable of being transported by carrier aircraft.

3.13 MISSION DURATION. Mission duration of 7 days shall be used to size the orbiter for self sustaining lifetime (from lift-off to landing) for a crew of four in accordance with Section 2.5. The orbiter design shall not preclude the capability to extend the orbital stay time up to a total of 30 days by adding expendables.

3.14 UNMANNED FLIGHT. (Deleted). All Space Shuttle orbital Flights shall be manned.

3.15 LAUNCH RATE. (Deleted). Refer to the currently approved Program Directive on Controlled Milestones.

3.16 OPERATIONAL DATES. (Deleted). Refer to the currently approved Program Directive on Controlled Milestones.

3.17 ORBITER VEHICLE ATTITUDE CONSTRAINTS. While the payload bay doors are open the orbiter will provide heat removal from the payload up to 21,500 BTU/hr in addition to the orbiter heat load. The addition of a radiator kit will increase the orbiter heat rejection and provide heat removal from the payload up to 29,000 BTU/hr. The radiator kit is comprised of two radiator panels added to the aft section of the Orbiter payload bay doors and the weight will be chargeable to the payload. With proper water storage and thermal conditioning before pointing the payload bay in the following typical attitudes, the minimum durations that the orbiter will maintain attitude holds are:

Payload Bay Viewing	Without Radiator Kit	With Radiator Kit
Deep Space (Non 3 Axis Inertia-1)	**>160 Hrs	**>160 Hrs
Deep Space, Stellar (3 Axis Inertial)	33 Hrs	33 Hrs
Direct .Earth	**18 Hrs	**30 Hrs
Direct Solar (3 Axis Inertial)	12 Hrs	16 Hrs

**For beta angles (orbit plane relative to the solar vector) in the range of 60 degrees to 90 degrees with worst case thermal orientation (other than 3 axis inertial holds) the orbiter shall be designed for repeated cycles of a minimum 6 hours attitude hold with no attitude constraints, followed by a maximum of 3 hours thermal conditioning. The hold times shown are cumulative times for the 6 hours hold periods.

These hold times can be extended by the selection of pre-mission variables such as vehicle orientation and orbital parameters.

A maximum of 12 hours of pre-entry thermal conditioning is required.

3.18 ORBITAL POINTING. The orbiter vehicle shall be capable of pointing a vector defined in th4-? navigation base-fixed axis system to day ground or celestial object with an accuracy of ±0.5 degrees.

4.0 ORBITER/PAYLOAD INTERFACE REQUIREMENTS.

4.1 PAYLOAD DEFINITION. Payloads referred to throughout this document are construed as the collective grouping of space hardware items such as: Spacelab experiments, research equipment, satellites, support modules, adapters and fueled transfer stages or equipment, into appropriate composite flight packages. For definition of Shuttle/orbiter payload accommodations, refer to Space Shuttle System Payload Accommodations Document. In the interest of maintaining minimum interface, (clean interface philosophy), payload designs should, where possible be self-sufficient systems, capable of checkout before installation in the orbiter and adaptable to standardized interface concepts jointly developed between payloads and Space Shuttle.

4.2 CHECKOUT. Payload performance testing and payload system checkout will be required prior to installation. Payload checkout while on the launch pad will be minimized and physical access to the payload will be limited. On-orbit status checks of the payload will be provided via the orbiter prior to release and/or retrieval.

4.3 DATA MANAGEMENT. The Orbiter shall provide standard displays and controls for monitoring the safety status of the payload. The payload shall provide to the Orbiter, at the interface, such information concerning the status or condition of the payload as is necessary to insure safe vehicle operation. Digital discrete, and analog signals shall be conditioned by the payload and supplied to the Orbiter Vehicle. Such equipment and capability shall be chargeable to the payload. Payload unique control and display accommodation with the Orbiter cabin shall be chargeable to the payload. A minimum standard interface shall be provided to exchange data for safety and payload status checks, and vehicle and operational parameters, such as navigation, guidance and control. Additional support may be feasible during certain operational modes.

4.4 PAYLOAD COMMUNICATION. The Orbiter shall provide direct and relay telemetry command and two-way voice capability with attached payloads and with released payloads. The Orbiter shall be capable of receiving and displaying limited payload data including video information and the RF downlink shall provide for relay of those limited payload data to the ground for both attached payloads and for released payloads.

4.5 PAYLOAD SAFETY. Space Shuttle payload elements shall insure elimination or control of payload design and operational hazards to the Space Shuttle System, other payloads and personnel. Safe payload operation with a minimum dependence on the Orbiter and crew for safing actions is a Space Shuttle goal. Requirements which are to be met by payloads are defined in the NASA "Safety Policy and Requirements for Payloads Using the Space Transportation System."

4.6 CONTAMINATION. The Orbiter Vehicle shall be designed to minimize the generation, introduction and accumulation of contaminants within the cabin, payload bay, and around attached payload modules. Payload and Orbiter RCS thruster exhaust shall not impinge or be reflected on deployed payloads or into the open payload bay. The total level of contamination within the payload bay from all sources shall be controlled to minimize the effects on payloads during all phases of Shuttle operations.

4.7 POWER. The Orbiter electrical power system shall provide for payload electrical energy allowance of not less than 50 kwh in the form of DC power to payloads through the Orbiter fuel cells. For missions with greater energy requirements, kits of approximately 840 kwh each will be provided outside the 15 ft. by 60 ft. (4.5xl8.2 meters) clear payload volume and will be chargeable to payload. Power supplied by the Orbiter for payload on orbit consumption will be limited to 7 kw average and l@? peak. (maximum duration peak power levels will be limited to 15 minutes duration at no less than 3 hour intervals.)

4.8 PAYLOAD POINTING. For payload pointing purposes, the orbiter GN&C system shall be capable of interfacing with a payload supplied and payload mounted attitude sensor. Provided that the accuracy of this sensor is equivalent to that of the Orbiter IMU, the Orbiter shall be capable of pointing a Vector defined in the sensor-fixed axis system to any ground or c4,ic-st3.cil (celestial???) object with an accuracy of +/-O.5 degrees. For payload pointing requirements beyond the capability of the Orbiter, the Orbiter GN&C system shall also be capable of interfacing with a compatible payload supplied and payload mounted stability and control system.

4.9 RENDEZVOUS AND DOCKING. The Orbiter Vehicle shall have an onboard capability to rendezvous and dock with an in-plane cooperative target or a passive stabilized orbiting element displaced up to 300 n. mi. (555 km). for Orbiter Vehicle preplanned docking missions, the docking mechanism will be installed in the payload bay. The weight of the docking mechanism and associated attachment fittings shall be chargeable to the payload.

4.10 PAYLOAD ATTACHMENT. The Orbiter shall provide standard discrete attachment points for mounting payloads. These attachment points shall be located along the payload bay, to accommodate different payload lengths and to allow for random order retrieval of multiple payloads.

4.11 PAYLOAD DEPLOYMENT AND RETRIEVAL MECHANISM. The orbiter shall provide a payload deployment and retrieval mechanism which shall be stowed outside the 60 ft. (18.2 meters) length by 15 ft. (4.5 meters) diameter payload volume. This mechanism shall deploy the payload clear of the Orbiter mold line. Release of the payload from the deployment mechanism shall leave the payload and the orbiter with only small residual rates. Spin-up capability, if required, will be accomplished by the payload.

For retrieval, the Deployment and Retrieval Mechanism shall interface with payloads designed for retrieval and, after attachment of the mechanism to the payload, shall align the payload in the payload bay to accommodate secure stowage of the payload. Additionally, the Payload Deployment and Retrieval Mechanism shall be capable of supporting the payload in the deployed position under the attitude stabilization and docking loads.

4.12 PAYLOAD BAY VENTS. Provisions for venting the payload bay shall be provided by the Orbiter. This vent system shall minimize the impact of venting upon the attitude control system.

*Information changed by Revision 8

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4.13 PAYLOAD BAY ACCESS. The Orbiter and launch facility shall permit access to the payload bay for payload installation, service, and removal in the Orbiter flight preparation area and on the launch pad. Access for personnel and cargo to the payload bay shall also be available through the hatch, which interfaces the Orbiter crew compartment with the payload bay. Ground access to the payload bay with be limited to the period up to 8.5 hours before launch.

4.14 PROPULSIVE STAGES. The Orbiter design shall include provisions for fill, vent, drain and dump, of liquid propellants of propulsive stages.

4.15 ACOUSTIC ENVIRONMENT. The Orbiter Vehicle payload bay interior sound pressure level shall not exceed a maximum overall of 145 dB during liftoff sequence (T = 10 secs). and 137 dB during other mission phases. The spectral frequency distribution is shown in Table 4.1.

4.16 SHUTTLE/PAYLOAD RANDOM VIBRATION. The Space Shuttle Orbiter mid-fuselage/payload bay random vibration criteria is reflected by figure 4-4. The actual vibration input to payloads will depend on transmission characteristics of mid-fuselage; payload support structure and interactions with each payload's weight, stiffness, and c.g. Payload random vibration will result largely from direct acoustic induced vibration and will be unique for each payload configuration.

4.17 ELECTROMAGNETIC COMPATIBILITY. Payloads shall be designed and tested to be compatible with the Space Shuttle System. The Space Shuttle System will be designed and tested in accordance with JSC specifications SL-E-0001 and SL-E-0002.

Pages 19 thru 25; Figures 2-1, 2-2, 2-3, 3-1, 3-2, Table 4-1, and Figure 4-2 NOT IN

Appendix II
Space Shuttle Launch Information Data Base

Space Shuttle Launch Information Data Base

Mission #	Landing Location	Orbiter 102 launched on time	Orbiter 102 launch delay time	Orbiter 102 launch aborts	Orbiter 099 launched on time	Orbiter 099 launch delay time	Orbiter 099 launch aborts	Orbiter 103 launched on time	Orbiter 103 launch delay time	Orbiter 103 launch aborts	Orbiter 104 launched on time	Orbiter 104 launch delay time	Orbiter 104 launch aborts	Orbiter 105 launched on time	Orbiter 105 launch delay time	Orbiter 105 launch aborts	Major System or Function caused delay	Sub-system responsible for delay	Launch Delays from Weather @ Launch Site	Launch Delays from Weather @ Alt. Landing Site or Mission Control
STS 1	EAFB 23		2 Days														G & C	GPC timing		
STS 2	EAFB 23		34 Days														RCS/APU	FRCS oxidizer,APU lube oil, & minor delay for fuel cell Ox, Mux/DeMux		
STS 3	White Sands 17		1 Hr.														GSE	GN2 purge gas heater		
STS 4	EAFB 22	6/27/1982																		
STS 5	EAFB 22	11/11/1982																		
STS 6	EAFB 22				4/4/1983	74 Days											SSME	SSME fuel leak (cracked valve)		
STS 7	EAFB 15				6/18/1983															
STS 8	EAFB 22					17 Min.											Weather	17 minutes	17 Min	
STS 9	EAFB 17		28 Days														SRBs	Roll back & destack for nozzle replacements		
STS 41B	KSC 15				2/3/1984	5 Days											APU	3 APU's replaced precautionary		
STS 41C	EAFB 17				4/6/1984															
STS 41D	EAFB 17								2 Days	64 Days							GPC/MEC	GPC, GPC/SSME's, MEC for SRB firing command, & Range 6min-50 sec aircraft		
STS 41G	KSC 33				10/5/1984															
STS 51A	KSC 15								1 Day								Weather	Upper wind shear	1 Day	
STS 51C	KSC 15								1 Day								Weather	Freezing cold	1 Day	
STS 51D	KSC 33								55 Min.								Range	Ship in SRB recovery zone		
STS 51B	EAFB 17					2Min18Sec											GSE	LPS failure		
STS 51G	EAFB 23							6/17/1985												
STS 51F	EAFB 23						17 Days										SSME	SSME Coolant valve failure, Also one SSME shutdown in flight @ 5min.45sec. with ATO		
STS 51I	EAFB 23								3 Days								Weather, GPC, & Weather	Thunderstorms @ LC, #5GPC failed, &Weather with Range ship in SRB recovery area	3 Days	
STS 51J	EAFB 23											22 min. 30 sec.					MPS	LH2 prevalve issue		
STS 61A	EAFB 17				10/30/1985															
STS 61B	EAFB 22										11/26/1985									
STS 61C	EAFB 22			25 Days													SRB,GSE, Weather, GSE, Weather	SRB HPU, LO2 sys, weather @ TAL Sites, LO2 sys, Weather for heavy rain	??????	
STS 51L	N/A					6 Days											Weather, GSE, Weather, GSE	Weather @ TAL site, GSE orbiter hatch tool stuck, Weather @ SLF cross-wind, GSE HIM	??????	
STS 26	EAFB 17								1 Hr.38 Min.								Crew sys, Weather	Crew suit cooling fuses & upper winds	1 Hr & 38 Min	
STS 27	EAFB 17											1 Day					Weather	Weather visibility & winds	1 Day	
STS 29	EAFB 22								1 Hr.50Min.								Weather	Weather Fog & upper wind	1 Hr & 50 Min	
STS 30	EAFB 22												6 Days				MPS, Weather	MPS LH2 recirc pump & leak @ET/Orb disconnect and Weather @ SLF/ visibility & wind	????	
STS 28	EAFB 17	8/8/1989																		
STS 34	EAFB 23											6 Days					SSME, Weather	SSME Controller & Weather @SLF	?????	
STS 33	EAFB 4								2 Days								SRB	Intg. Electronics assemblies		
STS 32	EAFB 22		1 Day														Weather	Weather @ LS		1 Day ??
STS 36	EAFB 23											6 Days					Crew, Weather, Range, Weather	Crew sick, weather bad, Range computer & weather again	????	
STS 31	EAFB 22								14 Days								APU	APU replaced		
STS 41	EAFB 22							10/6/1990												
STS 38	KSC 33											107+ Days					MPS	LH2 Leak @ ET/Orb disconnect required roll-back destack & received hail damage in transfer & handling damage		

Space Shuttle Launch Information Data Base Continued

Space Shuttle Launch Information Data Base

Mission #	Landing Location	Orbiter 102 launched on time	Orbiter 102 launch delay time	Orbiter 102 launch aborts	Orbiter 099 launched on time	Orbiter 099 launch delay time	Orbiter 099 launch aborts	Orbiter 103 launched on time	Orbiter 103 launch delay time	Orbiter 103 launch aborts	Orbiter 104 launched on time	Orbiter 104 launch delay time	Orbiter 104 launch aborts	Orbiter 105 launched on time	Orbiter 105 launch delay time	Orbiter 105 launch aborts	Major System or Function caused delay	Sub-system responsible for delay	Launch Delays from Weather @ Launch Site	Launch Delays from Weather @ Alt. Landing Site or Mission Control
STS 35	EAFB 22		185 Days														GSE, MPS, Payload, MPS, Weather	LH2 leak in GSE, LH2 leak @ ET/Orb disconnect, payload hardware failure, LH2 leak in MPS prevalve cover seal, then 21min. for weather on launch day	??????	
STS 37	EAFB 33										4/5/1991									
STS 39	KSC 15								50 Days								Orb.Mech, SSME	Roll-back for Orbiter ET Door hinge replacement, SSME HPOTP transducer & cable replacement		
STS 40	EAFB 22		14 Days														MPS, GPC, Hyd/OMS/ RCS, & G&C	MPS transducer failure concern, Mux/De-Mux failure that controls OMS/RCS/Hydraulic functions, & IMU failure		
STS 43	KSC 15											10 Days					Ele Sys., SSME, Cabin Press, Weather @ SLF	ET/Orb Sep electronic sys. Failure, SSME controler failure, cabin press valve concern & weather @ SLF for RTLS	??????	
STS 48	EAFB 22								14 Min.								Gr. Com	Faulty Ground communication link between Launch site and Mission Control		
STS 44	EAFB 5											5 Days					Payload, GSE	Failed IMU in Upper Stage, 13 Min delay for LO2 Repl valve repair		
STS 42	EAFB 22								1 Hr.								Weather	Weather	1 HR	
STS 45	KSC 33											1 Day					MPS	LO2 & LH2 leakage in Orb.Aft		
STS 49	EAFB 22														34 Min		Weather	Weather @ TAL site		34 Min
STS 50	KSC 33		5 Min.														Weather	Weather	5 Min	
STS 46	KSC 33										7/31/1992									
STS 47	KSC 33													9/12/1992						
STS 52	KSC 33		1 Hr.53Min.														Weather	Weather @ SLF (wind) & TAL (visibility)		1 Hr & 53 Min
STS 53	EAFB 22								1 Hr. 25Min.								Weather	ET ice buildup reduction	1 Hr & 25 Min	
STS 54	KSC 33														7 Min.		Weather	Upper Atm. Winds	7 Min	
STS 56	KSC 33								2 Days								MPS	Orb MPS HiPt bleed valve indication		
STS 55	EAFB 22			35 Days													SSME	SSME HiPress Turbopumps obs tip-seal retainers		
STS 57	KSC 33													6/21/1993						
STS 51	KSC 15									57 Days							GSE, SRB, & SSME	Hold down & umb. PIC failure, SRB-HPU failure, Abort from SSME faulty fuel sensor		
STS 58	EAFB 22		4 Days														Weather, Range	Delayed 2 Hrs for bad weather then scrubed for Range safety failure	2 Hrs	
STS 61	KSC 33														1 Day		Weather	Weather @ SLF	1 Day	
STS 60	KSC 15							2/3/1994												
STS 62	KSC 33	3/4/1994																		
STS 59	EAFB 22													4/9/1994						
STS 65	KSC 33	7/8/1994																		
STS 64	EAFB 4							9/9/1994												
STS 68	EAFB 22															43 Days	SSME	SSME HPOT temperature redline		
STS 66	EAFB 22										11/3/1994									
STS 63	KSC 15								1 Day								G&C	G&C IMU failure		
STS 67	EAFB 22													3/2/1995						
STS 71	KSC 15											3 Days					Weather	Weather for Launch	3 Days	
STS 70	KSC 33								55 Sec.								ET	ET Range Safety Reciever for SRB's		
STS 69	KSC 33														7 Days		Ele Power	Fuel Cell failure		
STS 73	KSC 33		7 Days														SSME, Weather	SSME Lox duct thickness concern	????	
STS 74	KSC 33											1 Day					Weather	Weather @ TAL site		1 Day
STS 72	KSC 15													1/11/1996						
STS 75	KSC 33	2/22/1996																		
STS 76	EAFB 22										3/22/1996									
STS 77	KSC 33													5/19/1996						
STS 78	KSC 33	6/20/1996																		
STS 79	KSC 15										9/16/1996									
STS 80	KSC		2 Min.														MPS, SSME	LH2 leakage in aft comp.		

Space Shuttle Launch Information Data Base Continued

Space Shuttle Launch Information Data Base

Mission #	Landing Location	Orbiter 102 launched on time	Orbiter 102 launch delay time	Orbiter 102 launch aborts	Orbiter 099 launched on time	Orbiter 099 launch delay time	Orbiter 099 launch aborts	Orbiter 103 launched on time	Orbiter 103 launch delay time	Orbiter 103 launch aborts	Orbiter 104 launched on time	Orbiter 104 launch delay time	Orbiter 104 launch aborts	Orbiter 105 launched on time	Orbiter 105 launch delay time	Orbiter 105 launch aborts	Major System or Function caused delay	Sub-system responsible for delay	Launch Delays from Weather @ Launch Site	Launch Delays from Weather @ Alt. Landing Site or Mission Control
STS 81	KSC 33										1/12/1997									
STS 82	KSC 33							2/11/1997												
STS 83	KSC 15		20 Min.														Cabin Pressure	Crew hatch seal leak required replacement		
STS 84	KSC 33										5/15/1997									
STS 94	KSC33	7/1/1997																		
STS 85	KSC 33							8/7/1997												
STS 86	KSC 15										9/25/1997									
STS 87	KSC 33	11/19/1997																		
STS 89	KSC 15													1/22/1998						
STS 90	KSC 33	4/17/1998																		
STS 91	KSC							6/2/1998												
STS 95	KSC 33							10/29/1998												
STS 88	KSC 15														1 Day		Orb Hydr.	Hydraulic System pressure low		
STS 96	KSC 15							5/27/1999												
STS 93	KSC 33	7/23/1999																		
STS 103	KSC 33								1 Day								Weather	Weather	1 Day	
STS 99	KSC 33														11 Days		Weather, MEC	Weather, MEC	????	
STS 101	KSC 15											25 Days					Weather	Weather @ SLF, Weather @ SLS & Pad, Weather @ TAL	25 Days	???
STS 106	KSC 15										9/8/2000									
STS 92	EAFB 22								6 Days								MPS, Weather, GSE	MPS Pogo valve failure, Weather @ pad, FOD on GSE	?????	
STS 97	KSC 15													11/30/2000						
STS 98	EAFB 22										2/7/2001									
STS 102	KSC 15							3/8/2001												
STS 100	EAFB 22													4/19/2001						
STS 104	KSC 15										7/12/2001									
STS 105	KSC 15							8/10/2001												
STS 108	KSC 15														1 Day		Weather	Weather @ Launch site	1 Day	
STS 109	KSC 33		1 Day														Weather	Weather @ Launch site too cold	1 Day	
STS 110	KSC 33											4 Days					GSE	LH2 sys leak in vent sys		
STS 111	EAFB 22														6 Days		Weather, OMS	Weather , OMS GN2 sys failure	???	
STS 112	KSC											5 Days					Weather	Weather @ JSC		5 Days
STS 113	KSC 33														12 Days		Orb GO2 sys, Weather	Orb. GO2 sys hose leak in mid-body, Weather @TAL site		???
STS 107	N/A	1/16/2003																		
Totals:	61 flights landed @ primary landing site	17 Launch on time	276 Days + 3 Hrs 20 Min.	60 Days from 2 Aborts	6 launch on time	85 Days + 19 Min 18 Sec	17 Days from 1 Abort	18 launch on time	83 Days + 7 Hrs. 2 Min. 55 Sec	121 Days from 2 Aborts	13 launch on time	174 Days + 2 Min 30 Sec	6 Days from 1 Abort	11 launch on time	39 Days + 41 Min	43 Days from 1 Abort		102 total Delays = 40 Weather + 46 Veh technical + 11 GSE + 3 Range + 2 Payload delays	??/65 Missions	??/65 Missions
Grand Total Information	61 of 113 flights landed @ primary landing site, or <u>50 required transpot back to launch site @ ~ $1 Million</u> <u>each.</u>	* 17 of 28 or 60.7% were on-time launched: Fleet avg=57.7%	OV-102 = 336 total Work Days launch delay in 11 events or an avg. of 30.5 work-days as its mean time to repair (MTTR)		* 6 of 10 or 60.0% were on-time launched: Fleet avg=57.7	OV-099 = 102 total Work Days launch delay in 4 events or an avg. of 25.5 work-days as its mean time to repair (MTTR)		* 18 of 30 or 60% were on-time launched: Fleet avg=57.7%	OV-103 = 204 total Work Days launch delay in 12 events or an avg. of 17 work-days as its mean time to repair (MTTR)		* 13 of 26 or 50% were on-time launched: Fleet avg=57.7%	OV-102 = 180 total Work Days launch delay in 13 events or an avg. of 13.8 work-days as its mean time to repair (MTTR)		* 11 of 19 or 57.9% were on-time launched: Fleet avg=57.7%	OV-102 = 82 total Work Days launch delay in 8 events or an avg. of 10.3 work-days as its mean time to repair (MTTR)					
						* **If Shuttle launch delay is less than one day (does not result in a scrub-turnaround), it is being documented as a launch-on-time in this analysis**														
		OV-102 Ao = MTBF/MTBF + MTTR = 363.4 / 363.4 + 30.5 = 92.3%																		
						Of 113 mission launch attempts, 65 Missions were launched the day scheduled or 57.5% and 13 of the 48 launch scrubs were weather related or 27%														
		OV-099 Ao = MTBF/MTBF + MTTR = 178.3 / 178.3 + 25.5 = 87.5%				**Therefore: Fleet Ao = OV-102 Ao + OV-099 Ao + OV-103 Ao + OV-104 Ao + OV-105 Ao / 5 Vehicles = 92.3% + 87.5% + 95.7% + 95.3% + 96.8% / 5 = 93.5% Fleet Availability**														
		OV-103 Ao = MTBF/MTBF + MTTR = 377.1 / 377.1 + 17 = 95.7%				Total Shuttle fleet Workdays of 15,831 - 904 lost days from delays (caused by scrub recycle) = 14,927 divided by the 112 flights yields an average ground processing flow of 133.3 Workdays per flight. Therefore, with an average MTBF for the fleet of 301.2														
		OV-104 Ao = MTBF/MTBF + MTTR = 277.8 / 277.8 + 13.8 = 95.3%																		
		OV-105 Ao = MTBF/MTBF + MTTR = 309.2 / 309.2 + 10.3 = 96.8%																		

Space Shuttle Launch Information Data Base Continued

Space Shuttle Launch Information Data Base

Mission #	Orbiter 102 & Mission Flt. Hrs.	Orbiter 102 Accum. Flights	Orbiter 099 & Mission Flt. Hrs.	Orbiter 099 Accum. Flights	Orbiter 103 & Mission Flt. Hrs.	Orbiter 103 Accum. Flights	Orbiter 104 & Mission Flt. Hrs.	Orbiter 104 Accum. Flights	Orbiter 105 & Mission Flt. Hrs.	Orbiter 105 Accum. Flights	Launch Pad #	Orbiter 102 & Pad Work day Exposure	Orbiter 102 & OPF Work day Exposure	Orbiter 102 & VAB Work day Exposure	Orbiter 099 & Pad Exposure Hrs.	Orbiter 099 & OPF Work day Exposure	Orbiter 099 & VAB Work day Exposure	Orbiter 103 & Pad Exposure Hrs.	Orbiter 103 & OPF Work day Exposure	Orbiter 103 & VAB Work day Exposure	Orbiter 104 & Pad Exposure Hrs.	Orbiter 104 & OPF Work day Exposure	Orbiter 104 & VAB Work day Exposure	Orbiter 105 & Pad Exposure Hrs.	Orbiter 105 & OPF Work day Exposure	Orbiter 105 & VAB Work day Exposure	Shuttle vehicle total ground-flow workdays.
STS 1	54.34806	1									LC 39A	104 Days	531 Days	33 Days													668 days
STS 2	54.22	2									LC 39A	70 Days	99 Days	18 Days													187 days
STS 3	192.0794	3									LC 39A	30 Days	55 Days	12 Days													97 days
STS 4	169.1586	4									LC 39A	29 Days	41 Days	7 Days													77 days
STS 5	122.2406	5									LC 39A	45 Days	48 Days	9 Days													102 days
STS 6			122.2403	1							LC 39A				115 Days	123 Days	6 Days										244 Days
STS 7			146.384	2							LC 39A				21 Days	34 Days	5 Days										60 Days
STS 8			145.1453	3							LC 39A				25 Days	26 Days	4 Days										55 Days
STS 9	247.79	6									LC 39A	34 Days	82 Days	12 Days													128 Days
STS 41B			191.2653	4							LC 39A				22 Days	52 Days	6 Days										80 Days
STS 41C			167.6686	5							LC 39A				18 Days	31 Days	4 Days										53 Days
STS 41D					144.9344	1					LC 39A							72 Days	123 Days	15 Days							210 Days
STS 41G			197.3925	6							LC 39A				22 Days	53 Days	5 Days										80 Days
STS 51A					191.7489	2					LC 39A							17 Days	34 Days	5 Days							56 Days
STS 51C					73.55639	3					LC 39A							20 Days	31 Days	5 Days							56 Days
STS 51D					167.9231	4					LC 39A							15 Days	53 Days	5 Days							73 Days
STS 51B			168.1461	7							LC 39A				15 Days	31 Days	4 Days										50 Days
STS 51G					169.6478	5					LC 39A							14 Days	37 Days	7 Days							58 Days
STS 51F			190.7572	8							LC 39A				31 Days	39 Days	5 Days										75 Days
STS 51I					170.295	6					LC 39A							22 Days	27 Days	7 Days							56 Days
STS 51J							97.74389	1			LC 39A										34 Days	84 Days	14 Days				132 Days
STS 61A			168.7475	9							LC 39A				14 Days	35 Days	4 Days										53 Days
STS 61B							165.0803	2			LC 39A										15 Days	27 Days	4 Days				46 Days
STS 61C	146.0642	7									LC 39A	34 Days	101 Days	8 Days													143 Days
STS 51L			0.020278	10							LC 39B				28 Days	30 Days	5 Days										63 Days
STS 26					97.00306	7					LC 39B							88 Days	221 Days	13 Days							322 Days
STS 27							105.0936	3			LC 39B										30 Days	196 Days	10 Days				236 Days
STS 29					119.6478	8					LC 39B							38 Days	100 Days	11 Days							149 Days
STS 30							96.94111	4			LC 39B										43 Days	79 Days	11 Days				133 Days
STS 28	121.0022	8									LC 39B	25 Days	190 Days	12 Days													227 Days
STS 34							119.6556	5			LC 39B										50 Days	95 Days	8 Days				153 Days
STS 33					120.1136	9					LC 39B							27 Days	114 Days	21 Days							162 Days
STS 32	261.01	9									LC 39A	33 Days	86 Days	10 Days													129 Days
STS 36							106.3061	6													35 Days	69 Days	6 Days				110 Days
STS 31					121.2683	10					LC 39B							39 Days	78 Days	9 Days							126 Days
STS 41					98.16778	11					LC 39B							32 Days	109 Days	8 Days							149 Days
STS 38							117.9086	7			LC 39A										85 Days	134 Days	26 Days				245 Days

Space Shuttle Launch Information Data Base Continued

Space Shuttle Launch Information Data Base

Mission #	Orbiter 102 & Mission Flt. Hrs.	Orbiter 102 Accum. Flights	Orbiter 099 & Mission Flt. Hrs.	Orbiter 099 Accum. Flights	Orbiter 103 & Mission Flt. Hrs.	Orbiter 103 Accum. Flights	Orbiter 104 & Mission Flt. Hrs.	Orbiter 104 Accum. Flights	Orbiter 105 & Mission Flt. Hrs.	Orbiter 105 Accum. Flights	Launch Pad #	Orbiter 102 & Pad Work day Exposure	Orbiter 102 & OPF Work day Exposure	Orbiter 102 & VAB Work day Exposure	Orbiter 099 & Pad Exposure Hrs.	Orbiter 099 & OPF Work day Exposure	Orbiter 099 & VAB Work day Exposure	Orbiter 103 & Pad Exposure Hrs.	Orbiter 103 & OPF Work day Exposure	Orbiter 103 & VAB Work day Exposure	Orbiter 104 & Pad Exposure Hrs.	Orbiter 104 & OPF Work day Exposure	Orbiter 104 & VAB Work day Exposure	Orbiter 105 & Pad Exposure Hrs.	Orbiter 105 & OPF Work day Exposure	Orbiter 105 & VAB Work day Exposure	Shuttle vehicle total ground-flow workdays.
STS 35	215.0856	10									LC 39B	157 Days	126 Days	16 Days													299 Days
STS 37							143.5456	8			LC 39B										22Days	97 Days	6 Days				125 Days
STS 39					199.3731	12					LC 39A							47 Days	116 Days	17 Days							180 Days
STS 40	218.2389	11									LC 39B	34 Days	74 Days	6 Days													114 Days
STS 43							213.3569	9			LC 39A										35 Days	60 Days	6 Days				101 Days
STS 48					128.4606	13					LC 39A							27 Days	78 Days	8 Days							113 Days
STS 44							166.8456	10			LC 39A										31 Days	67 Days	5 Days				103 Days
STS 42					193.2456	14					LC 39A							24 Days	75 Days	6 Days							105 Days
STS 45							214.1578	11			LC 39A										27 Days	55 Days	6 Days				88 Days
STS 49									213.2939	1	LC 39B													49 Days	217 Daysa	6 Days	272 Days
STS 50	331.5011	12									LC 39A	23 Days	108 Days	5 Days													136 Days
STS 46							191.2508	12			LC 39B										45 Days	61 Days	5 Days				111 Days
STS 47									190.5064	2	LC 39B													17 Days	77 Days	5 Days	99 Days
STS 52	236.9369	13									LC 39B	27 Days	72 Days	5 Days													104 Days
STS 53					175.3297	15					LC 39A							24 Days	247 Days	5 Days							276 Days
STS 54									143.6386	3	LC 39B													27 Days	55 Days	6 Days	88 Days
STS 56					222.14	16					LC 39B							22 Days	63 Days	10 Days							95 Days
STS 55	239.6664	14									LC 39A	73 Days	77 Days	5 Days													155 Days
STS 57									239.7483	4	LC 39B													51 Days	52 Days	16 Days	119 Days
STS 51					236.1864	17					LC 39B							70 Days	57 Days	8 Days							135 Days
STS 58	336.2089	15									LC 39B	28 Days	82 Days	17 Days													127 Days
STS 61									259.9769	5	LC 39B													33 Days	103 Days	6 Days	142 Days
STS 60					199.1561	18					LC 39A							22 Days	81 Days	5 Days							108 Days
STS 62	335.2781	16									LC 39B	19 Days	62 Days	5 Days													86 Days
STS 59									269.825	6	LC 39A													21 Days	67 Days	5 Days	93 Days
STS 65	353.9167	17									LC 39A	20 Days	62 Days	5 Days													87 Days
STS 64					262.8325	19					LC 39B							20 Days	125 Days	8 Days							153 Days
STS 68									269.7689	7	LC 39A													41 Days	59 Days	20 Days	120 Days
STS 66							262.5672	13			LC 39B										24 Days	110 Days	6 Days				140 Days
STS 63					198.4708	20					LC 39B							25 Days	71 Days	5 Days							101 Days
STS 67									399.1467	8	LC 39A													19 Days	81 Days	5 Days	105 Days
STS 71							235.3714	14			LC 39A										44 Days	115 Days	6 Days				165 Days
STS 70					214.3347	21					LC 39B							43 Days	63 Days	14 Days							120 Days
STS 69									260.4819	9	LC 39A													47 Days	81 Days	7 Days	135 Days
STS 73	381.8878	18									LC 39B	48 Days	100 Days	7 Days													155 Days
STS 74							196.5283	15			LC 39A										23 Days	76 Days	8 Days				107 Days
STS 72									214.0297	10	LC 39B													21 Days	64 Days	5 Days	90 Days
STS 75	377.6903	19									LC 39B	25 Days	64 Days	5 Days													94 Days
STS 76							221.28	16			LC 39B										22 Days	68 Days	6 Days				96 Days
STS 77									240.6694	11	LC 39B													27 Days	69 Days	5 Days	101 Days
STS 78	405.8083	20									LC 39B	19 Days	63 Days	7 Days													89 Days
STS 79							243.3244	17			LC 39A										25 Day	73 Days	17 Days				115 Days
STS 80	423.8883	21									LC 39B	33 Days	80 Days	6 Days													119 Days

Current Space Shuttle System “Shortfalls Assessment”

Space Shuttle Launch Information Data Base Continued

Space Shuttle Launch Information Data Base

Mission #	Orbiter 102 & Mission Flt. Hrs.	Orbiter 102 Accum. Flights	Orbiter 099 & Mission Flt. Hrs.	Orbiter 099 Accum. Flights	Orbiter 103 & Mission Flt. Hrs.	Orbiter 103 Accum. Flights	Orbiter 104 & Mission Flt. Hrs.	Orbiter 104 Accum. Flights	Orbiter 105 & Mission Flt. Hrs.	Orbiter 105 Accum. Flights	Launch Pad #	Orbiter 102 & Pad Work day Exposure	Orbiter 102 & OPF Work day Exposure	Orbiter 102 & VAB Work day Exposure	Orbiter 099 & Pad Exposure Hrs.	Orbiter 099 & OPF Work day Exposure	Orbiter 099 & VAB Work day Exposure	Orbiter 103 & Pad Exposure Hrs.	Orbiter 103 & OPF Work day Exposure	Orbiter 103 & VAB Work day Exposure	Orbiter 104 & Pad Exposure Hrs.	Orbiter 104 & OPF Work day Exposure	Orbiter 104 & VAB Work day Exposure	Orbiter 105 & Pad Exposure Hrs.	Orbiter 105 & OPF Work day Exposure	Orbiter 105 & VAB Work day Exposure	Shuttle vehicle total ground-flow workdays.
STS 81							244.9417	18			LC 39B										24 Days	62 Days	5 Days				91 Days
STS 82					239.6358	22					LC 39A							26 Days	147 Days	5 Days							178 Days
STS 83	95.22722	22									LC 39A	24 Days	73 Days	6 Days													103 Days
STS 84							221.3464	19			LC 39A										21 Days	77 Days	4 Days				102 Days
STS 94	376.7667	23									LC 39A	21 Days	53 Days	7 Days													81 Days
STS 85					283.3131	23					LC 39A							23 Days	102 Days	5 Days							130 Days
STS 86							259.37	20			LC 39A										29 Days	60 Days	5 Days				94 Days
STS 87	376.5836	24									LC 39B	22 Days	94 Days	5 Days													121 Days
STS 89									376.5836	12	LC 39A													26 Days	202 Days	7 Days	235 Days
STS 90	381.8494	25									LC 39B	24 Days	80 Days	5 Days													109 Days
STS 91					235.9169	24					LC 39A							29 Days	168 Days	4 Days							201 Days
STS 95					213.7489	25					LC 39B							29 Days	76 Days	5 Days							110 Days
STS 88									283.3131	13	LC 39A													37 Days	187 Days	5 Days	229 Days
STS 96					235.2325	26					LC 39B							30 Days	122 Days	12 Days							164 Days
STS 93	118.8383	26									LC 39B	43 Days	223 Days	5 Days													271 Days
STS 103					191.1928	27					LC 39B							36 Days	141 Days	9 Days							186 Days
STS 99									269.6614	14	LC 39A													44 Days	257 Days	10 Days	311 Days
STS 101							236.6	21			LC 39A										50 Days	333 Days	8 Days				391 Days
STS 106							283.2042	22			LC 39B										22 Days	66 Days	5 Days				93 Days
STS 92					309.6736	28					LC 39A							31 Days	197 Days	10 Days							238 Days
STS 97									259.0161	15	LC 39B													26 Days	203 Days	5 Days	234 Days
STS 98							309.35	23			LC 39A										28 Days	73 Days	30 Days				131 Days
STS 102					307.8167	29					LC 39B							21 Days	84 Days	8 Days							113 Days
STS 100									285.5	16	LC 39A													23 Days	82 Days	5 Days	110 Days
STS 104							306.6	24			LC 39B										21 Days	82 Days	11 Days				114 Days
STS 105					285.2	30					LC 39A							31 Days	79 Days	8 Days							118 Days
STS 108									283.9167	17	LC 39B													34 Days	142 Days	6 Days	182 Days
STS 109	262.1858	27									LC 39A	32 Days	253 Days	8 Days													293 Days
STS 110							259.7122	25			LC 39B										28 Days	161 Days	6 Days				195 Days
STS 111									332.5989	18	LC 39A													33 Days	92 Days	7 Days	132 Days
STS 112							259.9789	26			LC 39B										25 Days	108 Days	6 Days				139 Days
STS 113									330.8106	19	LC 39A													35 Days	79 Days	9 Days	123 Days
STS 107	382.35	28									LC 39A																
Totals:	7217.821	28	1497.767	10	5805.566	30	5278.061	26	5122.486	19		1076 Days	2979 Days	164 Days	311 Days	454 Days	48 Days	964 Days	3019 Days	192 Days	838 Days	2488 Days	134 Days	611 Days	2169 Days	93 Days	15,831 Days
Grand Total Information	7,218Hrs. with 28 flts		1,498Hrs. with 10 flits		5,806Hrs. with 30 flts		5,278Hrs. with 26 flts		5,123Hrs. with 19 flits			If 6 of 7 days/wk are work days, avg. days @ pad/launch = 44.8			If 6 of 7 days/wk are work days, avg. days @ pad/launch = 36.3			If 6 of 7 days/wk are work days, avg. days @ pad/launch = 37.5			If 6 of 7 days/wk are work days, avg. days @ pad/launch = 37.6			If 6 of 7 days/wk are work days, avg. days @ pad/launch = 37.5			

Total continuous ground processing Work Days resulting in Launch-on-time (without scrub turnaround) for OV-102 was 1817 days in 15 flight groupings or a mean-time-between-failure (MTBF) = 363.4 Work-days

Total continuous ground processing Work Days resulting in Launch-on-time (without scrub turnaround) for OV-099 was 595 days in 3 flight groupings or a mean-time-between-failure (MTBF) = 178.3 Work-days

Total continuous ground processing Work Days resulting in Launch-on-time (without scrub turnaround) for OV-103 was 2640 days in 7 flight groupings or a mean-time-between-failure (MTBF) = 377.1 Work-days

Total continuous ground processing Work Days resulting in Launch-on-time (without scrub turnaround) for OV-104 was 1389 days in 5 flight groupings or a mean-time-between-failure (MTBF) = 277.8 Work-days

Total continuous ground processing Work Days resulting in Launch-on-time (without scrub turnaround) for OV-105 was 1546 days in 5 flight groupings or a mean-time-between-failure (MTBF) = 309.2 Work-days

Appendix III
Space Shuttle Fluids Overview Matrix

SHUTTLE VEHICLE SERVICING FLUIDS

CHEMICAL AND PHYSICAL CHARACTERISTICS
CONTROLLED BY REFERENCE DOCUMENT
SE-S-0073 Revision G (6-23 CHANGE NO. 77)

SERVICING Fluid	Ref. Table SE-S-0073	Shuttle Sub-system Application			Maximum Sub-system Cleanliness Level Req'd	Main Propulsion (Orbiter, ET and SSME)	Aft Propulsion Orbit Maneuvering and Reaction Control	Reaction Control	Auxiliary Power Unit - Orbiter (APU)	Auxiliary Power Unit - SRB (APU)	SSME and Orbiter Hydraulic	SRB Hydraulic	Fuel Cells/Cryo	Environmental and Thermal Control / Life Support	Purge, Vent, and Drain	~ # of unique sub-systems requiring service each flight	~ # of individual interfaces requiring service (connect & disconnect) for each flight (not including multiple ground stations)	Revised R col values DRAFT
		Operational	Assembly	Cleaning Verification & Testing		|--------------------------- Shuttle Sub-system Identification --------------------------|												
Propellant Pressurizing Agent, Helium	6.3-1	X		X	100 A	X (100A)	X (200)	X (200)	X (100)	NA	NA	X (100)	X (200A)	X (300A)		17		
Liquid Oxygen	6.3-2	X			800 A	X (800A)										1		
Gaseous Nitrogen	6.3-3	X	X	X	100 A	X (100A)	X (200)	X (200)	X (100)	X (100)	X (200)	X (200)				6	20	20
Gaseous and Liquid Oxygen	6.3-4	X			200A								X (200A)	X (200A)		2	10	5
Gaseous and Liquid Nitrogen	6.3-5	X		X	200A								X (200A)	X (200A)	X (Class 5,000)	5		
Gaseous and Liquid Hydrogen	6.3-6	X			200	X (400)							X (200)			4	10	5
Hydraulic Fluid	6.3-7	X			190						X (190)	X (190)				7	15	7
Water (Grade A or B)	6.3-8	X		X	100/200A	X (1000)	X (200A)	X (200A)	X (100)	X (100)	X (200)	X (200)		X (200A)		3		
Propellant, Monomethylhydrazine	6.3-9	X			200		X (200)	X (200)								5		
Propellant, Nitrogen Tetroxide (MON-3)	6.3-10	X			200A		X (200A)	X (200A)								5		
Propellant, Hydrazine	6.3-11	X		X	100				X (100)	X (100)						7		
Argon	6.3-12	X	X		100A	X (100A)	X (200)	X (200)	X (100)	NA			X (200A)	X (100A)	X (Class 5,000)	2		
Propellant, Mixed Oxides of Nitrogen (Deleted)	6.3-13															0		
Lubricating Oil	6.3-14	X			300				X (300)	X (300)						7		
Conditioned Air - Purge, Vent, and Drain	6.3-15	X		X	Class 5,000	X (1000)									X (Class 5,000)	5		
Potable Water	6.3-16	X			300									X (300)		1		
Carbon Dioxide	6.3-17	X		X	100	NA								X (100)		0		
Ammonia	6.3-18	X			300A									X (300A)		2		
Biocide Flush Fluid	6.3-19	X			300									X (300)		1		
Refrigerant 21 (New and Recycled)	6.3-20	X		X	300									X (300)		3		
Avionics Fire Extinguishing Fluid	6.3-21	X												NA		2		
Conditioned Air - ECS	6.3-22	X			Class 100,000										X (Class 100,000)	5		
Fuel Cell Cooling Fluid	6.3-23	X			300								X (300)			3		
Breathing Oxygen	6.3-24			X	200A									X (200A)		0		
Isopropyl Alcohol	6.3-25			X	100/200A		X (200)	X (200)	X (100)	X (100)	X (100)	X (100)		X (200A)	X (200)	0		
Trichlorotrifluoroethane	6.3-26			X	200A	X (400A)	X (200A)	X (200A)					X (200A)	X (200A)	X (200A)	0		
Denatured Ethyl Alcohol	6.3-27			X	300									X (300)		0		
Trichloroethylene	6.3-28			X	800A	X (800A)										0		
Breathing Air Mixture	6.3-29			X	200A									X (200A)	X (200A)	0		
Airlock LCG Cooling Water	6.3-30	X			300									X (300)		2		
Ferry Flight WCL Fluid	6.3-31	X			300									X (300)		0		
Heat Transport Water	6.3-32	X		X	200/300A				X (200)	NA				X (300A)		3		
Shock Strut Hydraulic Fluid - Orbiter	6.3-33	X			190						X (190)	NA				0		
Missile Grade Air (Deleted)	6.3-34															0		
Refrigerant 114	6.3-35	X			300									X (300)		0		
Breathing Air (EMU Ground Test Only)	6.3-36			X	200A									X (200A)		0		
Nitric Oxide (Deleted)	6.3-37															0		
EMU Gaseous Oxygen	6.3-38	X			100A									X (100A)		2		
Propellant, Nitrogen Tetroxide (MON-10)	6.3-39															0		
RTG Heat Transport Fluid	6.3-40	X			300									X (300)		0		
APU/WSB Pre-Flush Lubricating Oil	6.3-41			X	300				X (300)	NA						0		
WMS Flush Fluid (1)	6.3-42			X	300									X (300)		0		
Waste Tank Cleaning Fluid (1)	6.3-43			X	300									X (300)		0		
Isopropyl Alcohol	6.3-44			X	400A	X (400A)										0		
WMS Servicing Fluid (1)	6.3-45			X	300									X (300)		0		
HCFC-225	6.3-46		X	X	200A	X (400A)	X (200A)	X (200A)					(200A)	X (200A)		0		
ZBA25	6.3-47			X	400	X (400)										0		
Refrigerant 124 (HCFC-124)	6.3-48	X		X	300									X (300)		2		
Perfluorohexane (PF-5060) (Lear Romec Quick Disconnects Only)	6.3-49			X	300									X (300)		0		
Vertrel MCA (Decafluoropentane [62%] and Trans-Dichloroethylene [38%]	6.3-50			X	200A	X (400A)		X (200A)					(200A)	X (200A)	X (200A)	0		
HFE-7100 (Methoxy-nonafluorobutane)	6.3-51			X	200A	X (400A)		X (200)					(200A)	X (200A)	X (200A)	0		
Vertrel XF (1,1,1,2,3,4,4,5,5,5-Decafluoropentane)	6.3-52			X	400A	X (400A)										0		
HCFC-225 G	6.3-53			X	200A	X (400A)		X (200A)					(200A)	X (200A)	X (200A)	0		
PGME/Water Azeotrope (1)	6.3-54	X			200						X (200)	NA				0		
	🟩	Note: Reference source does not address applications in Sub-systems control.														102 total		

Appendix IV
Hardware Dependability Influence on Propellant Cost/LCC Goals

Propellant Cost Influence In Achieving
Advanced Reusable Space Transportation Systems Cost/Pound Goals

STATEMENT OF THE CHALLENGE

With the goal being $100. /# of payload to orbit, the first reactions for most is to assume the goal is unrealistic; therefore, establish a range with a new must criteria of $500. /# to orbit. However, effectively applying all of our engineering experience and expertise, the space community may be surprised at the progress toward achieving this goal.

This challenging goal ($100. /# of payload to orbit) clearly suggests we must change "the way we do business" today. The program must establish the requirements to provide the controls required for achievement, i.e., the offline maintenance function alone represents ~50% of this goal regardless whether flying with normal boiling point or densified hydrogen and without considering the added cost of the purge gas requirements. The maintenance function must be scaled back by requiring the propulsion system fly considerably more missions between depot cycle and be more airline like the commercial gas turbines. This will not only drastically reduce the propellant cost, but, at the same time will bring down the logistics repair parts cost to be more inline with our goal of becoming more "airline like" the flight frequency will challenge us to provide propellant on site recycling our losses and at a much-reduced cost.

INTRODUCTION

Propellant cost is heavily driven by the way we are doing business, i.e., propulsion design philosophy. Design characteristics such as mixture ratio, design life, hardware depot cycle frequency, and propellant mass/ volume characteristics all influence a space transportation systems propellant cost. Also be aware that the user pays for all the losses and the price is a function of quantity used because there are fixed and variable cost associated with producing the product. Therefore, an example is provided using the Shuttle program Liquid Hydrogen cost of calendar year 2001 for a reference case. SSC testing represents a Depot cycle of the LH2 turbo-pump after 3 flights, the LO2 turbo-pump after 10 flights and 3 new SSME green-runs. The SSME requires depot cycle after 20 flights. This insight should be useful in establishing the Level I requirements for advanced space transportation systems.

STS LH2 USAGE FOR CALENDAR YEAR 2001

Liquid Hydrogen is used at MSFC, SSC, and KSC for the Shuttle program.

1. Quantity procured for MSFC was 406,406 #'s
2. Quantity procured for SSC was 5,793,771 #'s
3. Quantity procured for KSC was 2,213,738 #'s
4. Quantity actually flown by the Shuttle was 1,366,800 #'s in CY 2001 for 6 launches

Liquid Hydrogen purchased for KSC was by separate contract and the purchase price was $1.97/# with 61.74% of propellant launched. Remainder was transfer and storage losses. If this were the only added cost, the LH2 would be $3.19/# launched. If the concept of operation were to assume that the hydrogen flown were at triple point in stead of normal boiling point, the realized propellant launched is estimated to be only 40% that purchased which would drive the price to at least $4.93/# launched. However, this is only a part of the actual cost of propellant (densified hydrogen) when assessing the program as a whole.

Liquid Hydrogen purchased for MSFC and SSC was by separate contract and the purchase price because of the large quantity was ~ $1.09/# with NO propellant launched by Shuttle. This propellant was used for hardware depot maintenance (each SSME was refurbished and tested after ever flight during the calendar year 2001) and technology and reliability testing functions. Therefore, the maintainability burden designed into the hardware has a direct influence on the propellant logistics cost to operate a Space Transportation System, e.g., the greater time between depot maintenance cycles and hardware repair actions used in determining their operability requirements will greatly reduce the program recurring cost. To control and minimize the recurring cost, these operability requirements must be specified at Level I.

STS PAYLOAD COST PER POUND TO ORBIT FOR LH2 ONLY AND ACTUAL LH2 COST PER POUND LAUNCHED

When factoring in all uses of Liquid Hydrogen for the Shuttle propulsion program, it was determined that 8,413,915 #'s of Liquid Hydrogen were purchased and only 1,366,800 #'s flown on Shuttle in calendar year 2001. Therefore, only 16.24% of the propellant purchased was launched. This causes the actual Liquid Hydrogen cost to be $8.13/# launched. The propellant launched would have been 61.74% with **NO maintenance functions required** for the calendar year 2001 with 6 flights flown. **Liquid Hydrogen cost would have been $3.19/# launched or $14.54/ # of payload to orbit assuming a 50,000 # payload.** When **factoring in the maintenance cost of the propulsion systems the cost is $8.13/ # launched and $23.86/ # of a 50,000 # payload to orbit.**

A NOTIONAL SCENARIO FOR 3rd GEN REQUIREMENTS CONSIDERATION

To project a **scenario for 3rd Gen RLV with a SSTO vehicle and 20,000 #'s payload** the actual cost allocation would require $3.19 to $9.87/# for Liquid Hydrogen alone. Assume the vehicle was 1,113,636 #'s GLOW and was SSTO with a mass fraction of .88. This vehicle would require 140,000 #'s of Liquid Hydrogen and 840,000 #'s of Liquid Oxygen assuming a 6:1 mixture ratio propulsion system design.

LIQUID HYDROGEN CONSIDERATIONS:

Considering the losses for storage and transfer to load the vehicle with **normal boiling point hydrogen the cost of Liquid Hydrogen would be $3.19/# launched or $22.33/# of payload to orbit at 20,000#'s per flight**, but if it is assumed that the vehicle requires the hydrogen loaded at the triple point conditions, the added equivalent losses would drive the cost of **Densified Liquid Hydrogen to $4.93/# launched or $34.47/# of payload to orbit**. *These values do not include propulsion maintenance cost that will be required if not corrected by leveling a requirement at Level I to control recurring cost of the program.*

Therefore, if the level of hydrogen use for off-site engine depot maintenance remains the same, this **3rd Gen RLV will cost $4.94/ # actual launched cost and would represent $34.60/# of payload to orbit for the 20,000 # payload just to cover this maintenance function**. Assuming this depot maintenance function is not changed, this cost must be added to the launch site cost. **Therefore, assuming the 3rd Gen RLV used normal boiling point hydrogen, we will add the maintenance cost of $4.94/# of hydrogen to the launch cost of $3.19/# of hydrogen equaling $8.13/# of hydrogen launched or $56.93/# of payload to orbit assuming a 20,000 # payload**.

COST INSIGHT OF TECHNOLOGY CONCEPT ALTERNATIVE

However, concepts requiring the propellant be loaded in a densified state near the triple point instead of normal boiling point hydrogen will require more equivalent hydrogen at the launch site. This will drive the **Densified Liquid Hydrogen cost to $4.93/# launched or $34.47/# of payload to orbit for the launch site only.** Again if I assume the off site SSC + MSFC use were to remain the same and only using normal boiling point hydrogen but flying the vehicle at these **new triple point conditions, the added required quantity at KSC** would increase from **~226,757 #'s to ~350,000 #'s equivalent resulting in the cost being $9.87/# actual launched cost and would represent $69.09/# of payload to orbit for the 20,000 #payload.**

The above thinking does not include many factors that have not been determined. The concept of loading the flight tank with densified liquid hydrogen may require the removal of its sensible heat using cold hydrogen gas to avoid the large heat rise in the liquid during the loading. Also the flight tank will require pressure stabilization with cold helium gas during the loading and replenish operations to avoid tank collapse, as the Liquid Hydrogen will try to seek its equilibrium pressure of 1 psia. These functions were accomplished by using LH2 cold bath heat exchangers that will add another large quantity of Liquid Hydrogen at the launch site to accomplish this concept of operation.

LIQUID OXYGEN CONSIDERATIONS:

If a similar loss ratio is assumed for Liquid Oxygen, now determine the cost associated with the oxygen propellant for this 3rd Gen RLV scenario.

It was stated earlier that the 1,113,636 #'s GLOW was a SSTO with mass fraction of .88 with the mixture ratio of 6:1 and a payload of 20,000 #'s to orbit. Therefore, the Liquid Oxygen load would be 840,000 #'s. With the 61.74% propellant launched value used for Liquid Hydrogen being considered the same the Liquid Oxygen procured would be 1,360,544 #'s and at a price of $132.80/ton the cost would be $90,340.14 or **$0.11/# launched - $4.52/# of payload launched for the launch site cost**.

Again factoring in the propulsion maintenance cost would increase this cost.
The propellant purchased off site for this **maintenance and R&D function is 2.8 time that at KSC for Shuttle**. Therefore, using this ratio to determine the quantity purchased off site would be 3,809,524 #'s of Liquid Oxygen. Assuming the same price as KSC procurement would result in cost of **$252,952.38 or $0.30/# launched - $12.65/# of payload to orbit for this maintenance and R&D function.**

Therefore, combine these two functions to determine the cost of continuing business as usual would result in the following cost of $0.11/# launched at KSC plus the $0.30/# launched for maintenance would equal **$0.41/# launched or $17.22/# of payload to orbit for Liquid Oxygen.**

LIQUID OXYGEN AND HYDROGEN COMBINED CONSIDERATIONS:

Now combine the cost of both Liquid Hydrogen and Oxygen for this 3rd Gen RLV scenario:

1. Assume the use of **normal boiling point propellant only** and only that required at the launch site. LH2 @ $3.19/# launched or $22.33/# of payload to orbit plus LO2 @ $0.11/# launched or $4.52/# of payload to orbit = total of **$26.85/# of payload to orbit as launch site cost only.**
2. Consider the combined cost for the propulsion maintenance and R&D function off site. LH2 @ $4.94/# launched or $34.60/# of payload to orbit plus LO2 @ $0.30/# launched or $12.65/# of payload to orbit = total of **$47.25/# of payload to orbit considering only normal boiling point propellant use off site for the maintenance and R&D function.**
3. Now **combine the launch site and off site maintenance functions** to determine the actual **cost of doing business as with the Shuttle**. The LH2 cost will now be $3.19/# + $4.94/# = $8.13/# launched or $56.93/# of payload to orbit. The LO2 cost will be $0.11/# + $0.30/# = $0.41/# launched or $17.17/# payload to orbit. **When combining the two propellants** we have $8.13/# + $0.41/# = $8.54/# of propellant launched or $56.93/# + $17.17/# = **$74.10/# of payload to orbit cost using normal boiling point propellant.**
4. Assuming the use of densified LH2 only at the launch site, but business as usual for the maintenance function, the LH2 cost will now be $4.93/# + $4.94/# = $9.87/# launched or $69.07/# of payload to orbit. The LO2 cost will be $0.11/# + $0.30/# = $0.41/# launched or $17.17/# payload to orbit. **When combining the two propellants,** we have $9.87/# + $0.41/# = $10.28/# of propellant launched or $69.07/# + $17.17/# = **$86.24/# of payload to orbit. This resulting cost is using densified hydrogen at the launch site and normal boiling point propellant off site for maintenance functions.**

The desire to use densified liquid oxygen would result in a similar cost increase relationship for the LO2 propellant.

OTHER CONSIDERATIONS NOT INCLUDED IN THE ABOVE ASSESSMENT:

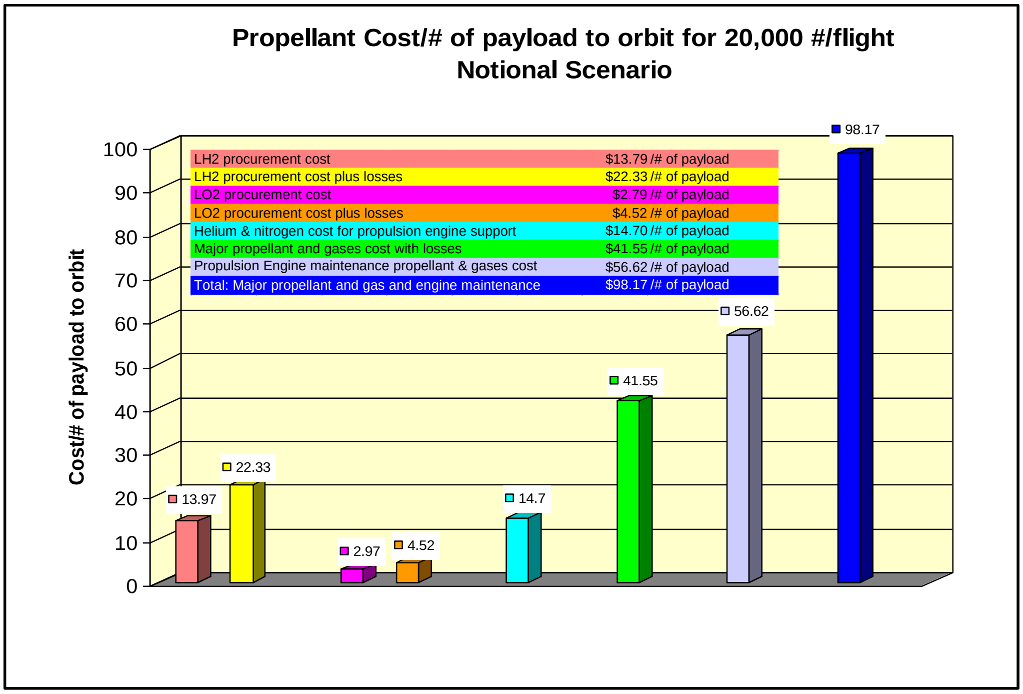
The above propellant cost assessment only represent ~80% of the propellant cost when working with cryogenics as we do business today. As an example, a data sample is provided to support this conclusion from SSC SSME operations during the FY 2000 period.

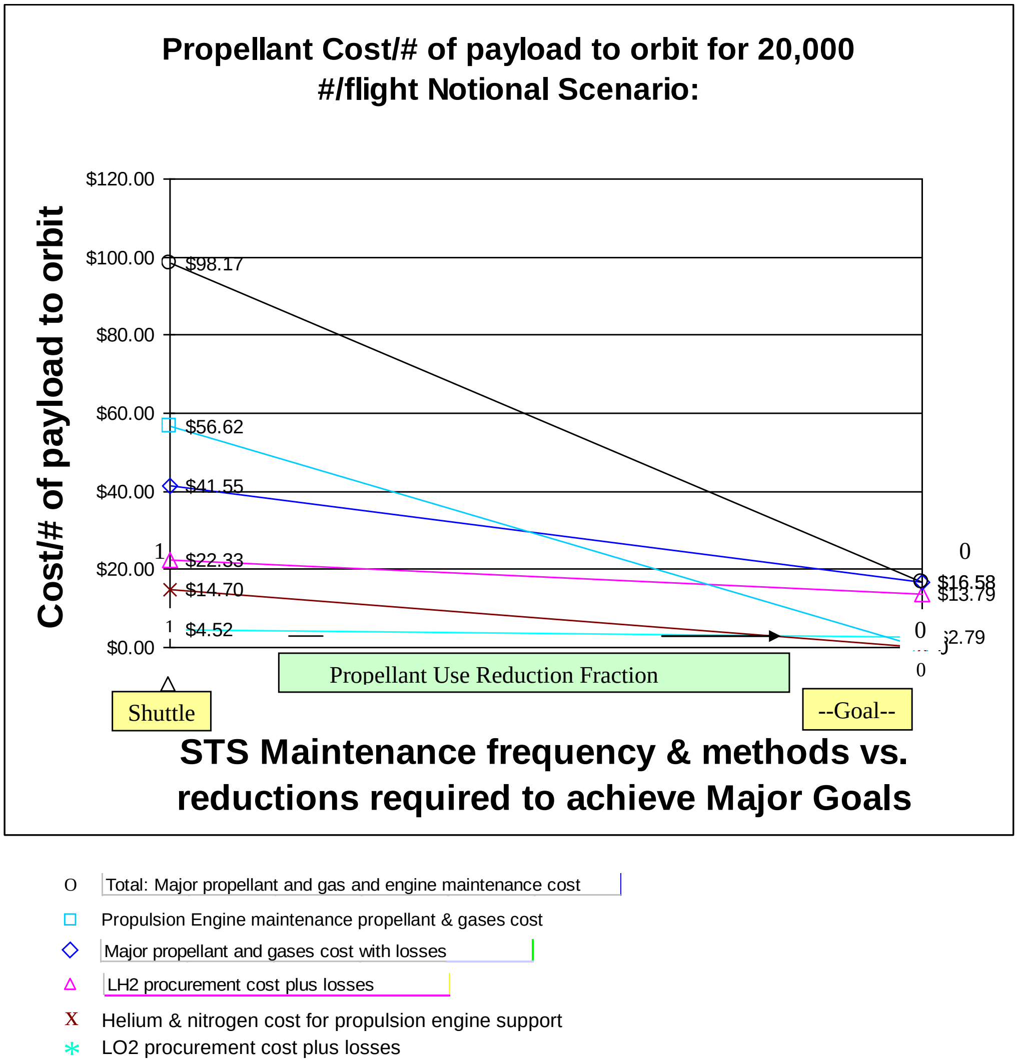
Liquid hydrogen cost = $7,314,922. ------- 70.67% of total propellant cost
Liquid oxygen cost = $1,323,150 ---------- 12.78% of total propellant cost
Gaseous Helium cost = $1,044,120 -------- 10.09% of total propellant cost
Liquid nitrogen cost = $668,230 ------------- 6.46% of total propellant cost

Liquid propellants = 83.45% and purge requirements represent 16.55% of total annual cost to support the SSME maintenance and R&D operation off site during FY 2000. Liquid hydrogen use during FY-2000 was 19.5% greater than CY-2001: therefore, the above cost is higher than CY-2001 but cost relationship should be considered the same. These purge gas cost will also be required at the launch site in similar ratios as SSC operation for the SSME operation.

CONCLUSIONS

To achieve the cost goal ($100. /# of payload to orbit), this analysis concludes the space community must change the way we are doing business today to be more inline with airline operations. The design life, time between depot cycles, and the hardware inherent reliability must all be improved and follow the leadership of the airline/aircraft industry. Suggest increasing the depot maintenance cycle time to be more airline like the commercial gas turbines, use combined cycle which induces air to replace some of the oxygen, consider moving to oxygen rich combustion for the early phase of flight, and drive to single stage to orbit, the propellant cost will be more in line with our objective goal. These improvements are required just to reduce the fluid commodity cost required to achieve the overall cost objective. Also the propellant cost of $74.10/# of payload to orbit does not include the gases required to support the cryogenic operation and this was 16.5% of the cost to do business at SSC. The desire of some to use densified propellants could increase the propellant cost to $86.24/# of payload to orbit plus a considerably higher cost for the gases. To safely use densified propellants will require a cold helium bottle submerged in the propellant tanks with the bubbling of helium to maintain the tank structure stability during ground servicing operations. Again this choice is directly opposite the desired cost reduction from today’s way of doing business.




Propellant Cost/# of payload to orbit for 20,000 #/flight Notional Scenario:
Cost/# of payload to orbit
$120.00
$100.00
$80.00
$60.00
$40.00
$20.00
$0.00
$98.17
$56.62
$41.55
1
$22.33
$14.70
1
$4.52
0
$16.58
$13.79
0
$2.79
0
Propellant Use Reduction Fraction
Shuttle
--Goal--
STS Maintenance frequency & methods vs. reductions required to achieve Major Goals
O Total: Major propellant and gas and engine maintenance cost
□ Propulsion Engine maintenance propellant & gases cost
◇ Major propellant and gases cost with losses
△ LH2 procurement cost plus losses
X Helium & nitrogen cost for propulsion engine support
✳ LO2 procurement cost plus losses

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
        - LH2 & GH2 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 GN2 purge (2)
        - Field joint heater system (10)
        - Ignition overpressure suppression & control system (one foot H2O coverage of top of exhaust opening) (2)
        - Ignition overpressure suppression & control H2O 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

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.

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	10 years or 100 flts/veh.	20+ years, but only 30 flts/veh. Max., but still counting	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 permitted less than 3 flights per year. Avg. 100 components replacement plus ~ 400 expendable or limited life parts. Application must be well understood so that the reliability requirements flow-down supports the design life after balancing the requirement with safety and maintainability.

Current Space Shuttle System "Shortfalls Assessment"

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	2. Propulsion Main Engine Life	55 starts/Depot cycle.	After 20+ years ops: SSME depot cycle 20, LO_2 turbo-pumps 10 & fuel turbo-pumps 3 flts	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.
A 1.2	3. Recurring cost:	$100.00/lb to LEO @ 28.8 degrees and 100 nmi	~ $10,000.00/lb to LEO Actual Shuttle recurring cost over the total 21 operating years = ~ $57.876 Billion. Over the 21 operating years 2,934,200 lbs has been delivered to various orbits. Ref. Appendix IX	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.

Current Space Shuttle System "Shortfalls Assessment"

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 & 5.4	4. Non-recurring cost:(DDT&E and Acquisition)	$5.0 Billion	$15.0 Billion	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.
R 3.2	5. Each vehicle flight rate:	10 flights/yr.	2.5-3 flights/yr.	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 replaced during the turnaround operation, and extensive servicing require (too many different fluids and too many interfaces along with the extensive support infrastructure), the achievable flight rate is ~ 2.5 per year.

Current Space Shuttle System "Shortfalls Assessment"

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	6. Fleet flight rate:	40 flights/yr. at ETR	10 flights/yr.	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 replaced during the turnaround operation, and extensive servicing require (too many different fluids and too many interfaces with the extensive support infrastructure), the achievable flight rate is ~ 2.5 per year.

Current Space Shuttle System "Shortfalls Assessment"

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 3.1 &3.9	7. Vehicle turnaround time:	160 hours	1296 hours Min.	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 replaced during the turnaround operation, and extensive servicing require (too many different fluids and too many interfaces along with the extensive support infrastructure), the achievable flight rate is ~ 2.5 per year. Because the integrity of systems are compromised to provide for parts change-out and to support turnaround operations, the STS must be recertified for each flight.
R 3.1 &3.9	8. Vehicle/System terminal countdown:	2 hours	8 hours plus	The initial design terminal countdown was 2 hours including main propellant loading, crew ingress and egress checks. The initial design requirement was 24 hours from standby status (VAB/T-0) which included this 2 hour terminal countdown. This requirement was deferred because of the added DDT&E cost to provide the automation for crew ingress/egress and MPS Lox transfer capacity needed.

Current Space Shuttle System “Shortfalls Assessment”

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	9. System performance to LEO	65,000 lbs at ETR @ 28.8 degrees and 100 nmi	55,000 lbs at ETR @ 28.8 degrees and 100 nmi	This shortfall 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 an additional $20,000,000./ET unit for a 6,000 pound weight reduction.
R 3.1/ S 4.2	10. Space flight rescue time:	24 hr. VAB/T-0	Not capable, but now being considered again since Columbia event.	Initial ground system design includes the capability to change out the payload at the pad, but 2 hour terminal countdown capability was not implemented and the lack of meeting the fleet flight rate caused a deferral of this requirement.
	11. STS Dependability/Safety	Not stated	Program has lost 14 flight crew and 2 ground members and two orbiters.	The initial design reliability was 0.98 for 100 missions of each orbiter. No requirements were established for loss of flight or ground crew members and the impact of insufficient component reliability and environment interaction was not sufficiently considered and understood.
D 2.2/ S 4.1	11.1 Loss of Vehicle	0.98	0.964 for the Orbiter 0.962 for the SRB	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 was not considered with proper risk reduction actions. Target metric value was deficient in determining its overall impact on program.

Current Space Shuttle System “Shortfalls Assessment”

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/ S 4.1	11.2 Flight system program reliability:	0.98 for 100 missions of each orbiter or 500 missions total for fleet of 5 orbiters.	0.964 for the Orbiter 0.962 for the SRB	The initial design was for the reliability of each orbiter to be 0.98 for 100 missions. 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 were not considered with proper risk reduction actions. 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.
D 2.3	11.3 Mission reliability:	The subject in general was controlled by NHB 5300.4	~0.96	All flight vehicle subsystems (except primary structure, thermal protection system, and pressure vessels) shall be established on an individual Sub-systems basis, but shall not be less than fail-safe. Safety, reliability, and maintainability were controlled separately by NHB 5300.4 (lD-1), August 1974.

Current Space Shuttle System "Shortfalls Assessment"

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	11.4 Maintainability:	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 and 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 and fuel turbo-pumps after every 3 flights	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, has balanced with safety and reliability, contributed to the large resultant cost per flight and the low flight rate. No specific maintainability requirements set.
R 3.7	11.5 Component replacement time or mean time to repair (MTTR)	No Requirement documented other than 160 hours turnaround	Example of SSME 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. 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.

Current Space Shuttle System “Shortfalls Assessment”

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 3.1 &3.9	11.6 Launch Availability:	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.	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.	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.
S 4.1 &4.2	11.7 Flight abort during ascent: Prevent Loss of Crew	Designed for: return-to-launch-site; abort-to-orbit; abort-once-around (RTLS/ATO/AOA)	Did not demonstrate RTLS or transatlantic landings (TAL’s) and ATO was required only once, but did not result in an aborted operation.	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.
S 4.1 &4.2	11.8 Flight abort from orbit: Prevent Loss of Crew	KSC prime, EAFB secondary, & several contingencies	3 landing sites used: (KSC, EAFB, and White Sands)	No abort was provided during the descent phase and an orbiter (102) and its crew were lost during re-entry.

Current Space Shuttle System "Shortfalls Assessment"

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 2.4/ R 3.1	12. Flight environment: Launch and Landing	95 percentile natural environment expected at operational locations	7 mile visibility and no rain	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.
R 3.1 &3.8	13. 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. was not provided; therefore, each mission is planned as a custom mission.

Current Space Shuttle System "Shortfalls Assessment"

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	14. 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. Lack of performance margin drives a custom redesign for payloads for each mission.

Current Space Shuttle System "Shortfalls Assessment"

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	15. 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.
R 3.9/ A 1.5/ R 3.6	16. Total number of sub-systems requiring servicing with dedicated ground systems, e.g., number of dif. Fluids, number of dif. Electrical supplies, etc.	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.	Not considered was a need to provide any control as 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 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.

Current Space Shuttle System "Shortfalls Assessment"

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	16. Total number of sub-systems requiring servicing with dedicated ground systems, e.g., number of dif. Fluids, number of dif. Electrical supplies, etc. *Con't*		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. Data bus and communication systems as well as unique instrumentation that have not been accounted for in this assessment.	

Current Space Shuttle System “Shortfalls Assessment”

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	17. Degree of custom build required to support each mission	The shuttle initial design requirement provided an allocation of 96 hours of the 160 turnaround for the orbiter turnaround including the payload installation a 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.

Current Space Shuttle System "Shortfalls Assessment"

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	18. Total number of manual functions required to determine and control critical flight functions, e.g., CG, fluid residuals content and purity, functionality of primary and backup system hardware	No Requirement documented other than (160 hours turnaround, 24 hr. notice to launch, and 40 flights/yr. with 4 vehicle fleet). Not considered as a need to provide any control and would be considered as over constraining.		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.
D 2.5	19. Launch on time (No launch scrubs)	No Requirement documented except 24 hr. notice to launch for space rescue and military needs.	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.	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.

Current Space Shuttle System "Shortfalls Assessment"

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 2.6	20. Materials, fluids, and designs properties and limitations well understood through failure with narrow tolerances	Not considered as a need to provide any control and would be considered as over constraining and would have drove up the DDT&E cost considerably.	Because the limits are not known, operational controls must provide margins to avoid unplanned events. Performance also carries an extra margin to allow for these uncertainties.	Program objectives were compromised because of these added limitations do to uncertainties.
A 1.7/ P 5.2	21. LCC must be well defined and understood by analysis without any allocations/assumptions so that the business case closes	No Requirement documented, but 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.	Shuttle NRC (DDT&E) = $15 billion and the RCC avg 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 Billion. Or a total LCC = $72.876 billion. These actual costs do not include any R&T cost prior to the STS ATP (1-5-72), e.g., SSME, TPS, etc.	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 put in place to provide the necessary control required.

Current Space Shuttle System "Shortfalls Assessment"

Attribute I D.	Program Objectives and Desired Attributes needed to Correct Shortfalls of Current Systems	Target Value	Actual Achieved	Critical Shortfalls Relative to Requirements
P 5.3	22. All technologies must be matured at the TRL-6 level or above and options must be available as backups where risk is moderate or above prior to start of acquisition.	No Requirement documented. DDT&E schedule and cost risks were not considered a necessity as we were still working to the Apollo paradigm.	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 control flight/ground systems	NASA started a major program with five major non-mature technologies and no technology backups. Also did not provide the margin in cost or schedule to account for this high risk approach.
S 4.3	23. All processes and operations must be compatible with environmental regulations and laws	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.	Stringent Environmental /OSHA requirements have been imposed since Shuttle ATP	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
R 3.6	24. Vehicle, payload, and ground systems integration functions must be compatible with all LCC requirements by analysis without any assumptions.	No Requirement documented other than (160 hours turnaround, 24 hr. notice to launch, and 40 flights/yr. with 4 vehicle fleet). Not considered as a need to provide any control and would be considered as over constraining.	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.	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	25. Easily Supportable (minimum support infrastructure required) and must be compatible with all LCC requirements by analysis without any assumptions	No Requirement documented other than (160 hours turnaround, 24 hr. notice to launch, and 40 flights/yr. with 4 vehicle fleet). Not considered as a need to provide any control and would be considered as over constraining.	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. 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.	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. Not considered a need to provide any control as 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 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.

Current Space Shuttle System "Shortfalls Assessment"

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	25. Easily Supportable (minimum support infrastructure required) and must be compatible with all LCC requirements by analysis without any assumptions *Con't*		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. Additionally there are data bus and communication systems as well as unique instrumentation that have not been accounted for in this assessment.	

Appendix VIII

SUMMARY OF ANNUAL SHUTTLE PAYLOAD DELIVERED OR RETRIEVED FROM SPACE

Table 1. Annual Summary of Space Shuttle Deployed and Retrieved Cargo

		Total Annual Payload Liftoff Mass (1)		**Deployed to Space**		**Deployed and Retrieved**		**Retrieved Only**	
Year		Metric Tons (mt)	Pounds (lbs.)	Metric Tons (mt)	Pounds (lbs.)	Metric Tons (mt)	Pounds (lbs.)	Metric Tons (mt)	Pounds (lbs.)
1981		13.43	29,601	0.00	0	0.00	0	0.00	0
1982		25.03	55,184	6.62	14,585	0.00	0	0.00	0
1983		62.36	137,476	27.19	59,940	1.45	3,192	0.00	0
1984		72.15	159,060	42.76	94,268	0.00	0	1.08	2,381
1985	(2)	110.20	242,956	46.91	103,417	1.01	2,217	0.00	0
1986		35.04	77,258	5.60	12,351	0.00	0	0.00	0
1987		0.00	0	0.00	0	0.00	0	0.00	0
1988	(2)	20.23	44,601	17.02	37,514	0.00	0	0.00	0
1989	(2)	70.47	155,361	59.60	131,397	0.00	0	0.00	0
1990	(2)	45.11	99,450	27.99	61,699	0.00	0	0.00	0
1991		88.37	194,820	56.62	124,820	1.84	4,046	0.00	0
1992		93.62	206,387	27.04	59,613	0.67	1,486	0.00	0
1993		87.39	192,655	30.31	66,826	4.61	10,161	5.25	11,572
1994		72.58	160,009	0.08	171	4.53	9,996	0.00	0
1995		75.40	166,224	21.69	47,812	4.52	9,957	0.53	1,166
1996		64.82	142,898	3.89	8,582	7.71	17,004	6.04	13,321
1997		79.57	175,429	9.49	20,920	4.86	10,724	6.77	14,915
1998		61.01	134,499	15.39	33,931	1.35	2,973	3.09	6,807
1999		38.88	85,704	23.92	52,731	0.00	0	2.52	5,564
2000		64.99	143,274	30.57	67,404	0.00	0	1.30	2,859
2001		81.02	178,619	38.17	84,158	0.00	0	5.51	12,150
2002		58.25	128,410	--	--	--	--	--	--
2003		11.03	24,325	--	--	--	--	--	--
2004		0.00	0	0	0	0.00	0	0.00	0
Total		**1330.94**	**2,934,200**	**490.86**	**1,082,139**	**32.55**	**71,756**	**32.09**	**70,735**

Note 1: Weights listed are those chargeable to payload; taken from "Space Shuttle Flight Weight Summary," in Space Shuttle Missions Summary; Book 2, Next 100 Flights; NASA JSC/DA8, Rev. S, May 2002.

Note 2: Does not include Dept of Defense mission payloads flown on the Space Shuttle system from 1985 through 1990.

Current Space Shuttle System "Shortfalls Assessment"

Appendix IX

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