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Designing for Annual Spacelift Performance

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DESIGNING FOR ANNUAL SPACELIFT PERFORMANCE

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ABSTRACT

This paper presents a methodology for approaching space launch system design from a total architectural point of view. This different approach to conceptual design is contrasted with traditional approaches that focus on a single set of metrics for flight system performance, i.e., payload lift per flight, vehicle mass, specific impulse, etc. The approach presented works with a larger set of metrics, including annual system lift, or “spacelift” performance. Spacelift performance is more inclusive of the flight production capability of the total architecture, i.e., the flight and ground systems working together as a whole to produce flights on a repeated basis. In the proposed methodology, spacelift performance becomes an important design-for-support parameter for flight system concepts and truly advanced spaceport architectures of the future. The paper covers examples of existing system spacelift performance as benchmarks, points out specific attributes of space transportation systems that must be greatly improved over these existing designs, and outlines current activity in this area.

INTRODUCTION

Design and analysis of space launch systems in the past have focused on the basics of the "rocket equation". Vehicle design parameters such as propellant mass, structural mass, payload mass, and propulsion metrics like specific impulse and thrust-to-weight ratios have dominated the design and analysis of launch systems. In today's highly competitive launch arena, however, launch system operations demand better performance in terms of vehicle utilization, flight rate and operations infrastructure costs.

The launch system must increasingly be thought of as a marriage between flight systems working efficiently with ground systems. This requires close attention to vehicle-ground system compatibility from conceptual design and analysis, through preliminary design and continuing through detailed design. This means conceiving flight designs and analyzing them not only in the context of their flight regime, but continually projecting the concepts in their operational spaceport environment. Early identification and control of potential ground processing bottlenecks, flight-to-ground system incompatibilities, and excessive infrastructure are becoming as important as controlling vehicle mass or thrust margin.

Satisfying the rocket equation is still a necessary, but no longer sufficient, criteria for the success of a launch system. Measures of performance that take into account the traditional rocket equation performance parameters, as well as the new parameters of launch system affordability, dependability and responsiveness, are needed. This paper suggests some ways to approach this new design environment, specifically, trading launch performance per flight against launch performance on an annual basis.

A CARGO AIRLIFT ANALOGY

To begin, suppose one had to design a cargo airlift system (perhaps for an overnight delivery or military airlift requirement). Two approaches could be employed: 1) design to the maximum payload fraction and size the flight system to the maximum payload that could be lifted in one flight for the farthest range, or 2) understand the necessary cargo lift requirement over an annual period and begin trading per-flight performance against the annual requirement to arrive at a required vehicle utilization level. Then the flight system can be designed to be compatible with advanced airport cargo handling systems that could achieve the required vehicle utilization rate.

For example, suppose that one system designed-in standardized cargo containers, while another system was designed to save the mass of the containers in an effort to maximize the amount of cargo lifted in one flight. In the latter scenario the flight line packs and loads the cargo items individually on the flight line (which would consume a lot of time on the ground). The design proposal incorporating the weight of the containers, however, allows loading and packing the many individual items offline followed by repeated, quick insertions of the containers, thus increasing overall flight production at the airport and a high level of vehicle utilization of the airliner. The annual performance of the whole system (flight and ground) would be maximized, even though a weight penalty existed in the flight system to carry the containers.

VIEWING SPACELIFT PERFORMANCE AS A DESIGN TRADE OPPORTUNITY

Spacelift architects are in a situation similar to the one previously described, not only in terms of the cargo operations function, but across all facets of space launch system design. From toxic commodity management to plume exhaust compatibility with the launch site, to electrical/avionics command and control autonomy, to purge system interfaces, and the built-in and tested-in dependability of flight hardware—these issues offer design trade opportunities that are particularly effective during conceptual and preliminary design.[1]

SPACELIFT PERFORMANCE BENCHMARKING

Before detailing a new “design-for-support” methodology for space launch, it is helpful to measure, or “benchmark”, the annual spacelift performance of today’s space launch industry as a whole. Ideally, benchmarks of affordability, dependability and responsiveness should be measured. A benchmarking survey and analysis of existing launch performance is currently underway

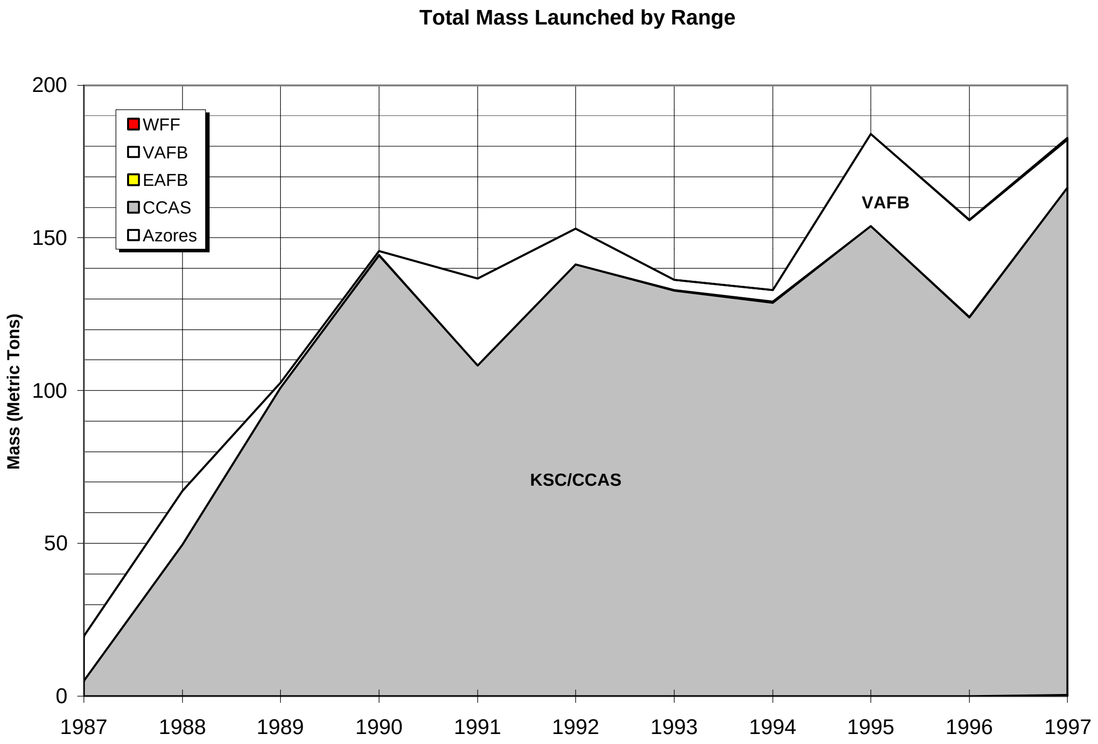


FIGURE 1—U.S. Spacelift Performance By Launch Area (1987-1997)

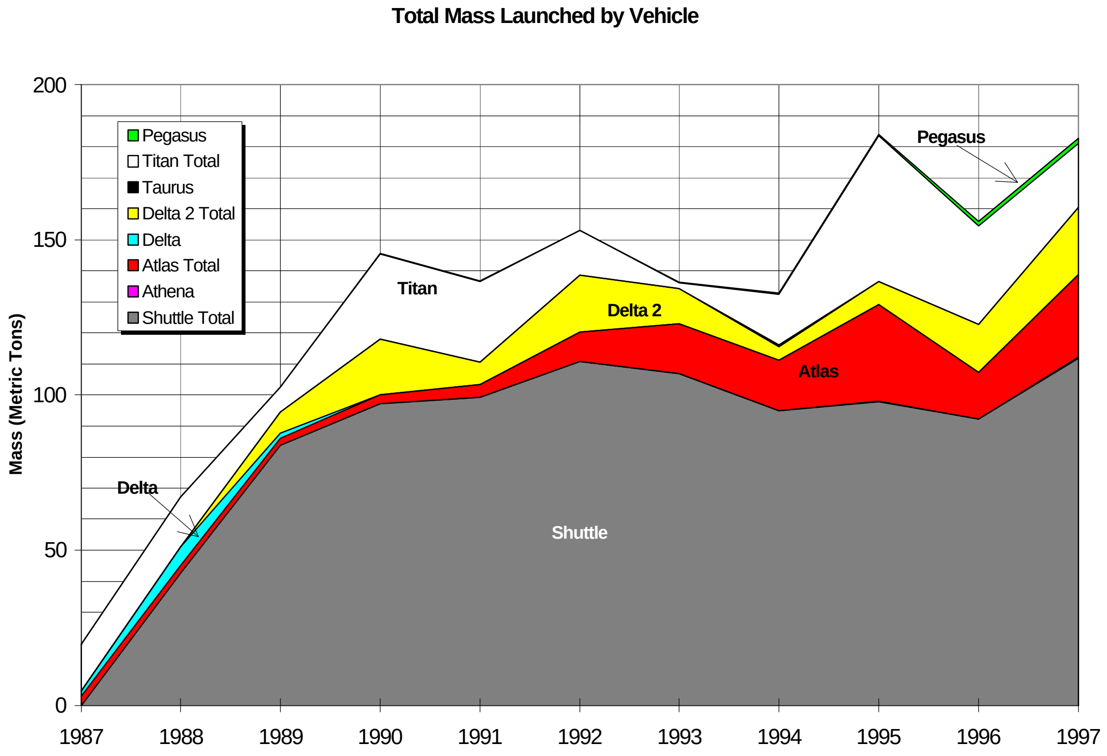
at the Kennedy Space Center as part of its Vision Spaceport Project. The objective is to develop a database of existing launch capabilities useful to spacelift performance comparisons. In particular, actual flight production information is being integrated with launch vehicle per-flight lift capability to derive an annual performance metric for the total "spacelift" capability of the launch system. Other metrics relevant to flight production that involve the attributes of operating cost, cycle time, as well as hardware and process dependability will be examined in more detail in the future. Due to the sensitive nature of cost and pricing information, attention is being given to total system responsiveness and dependability performance—two major attributes that are assumed to make up the recurring operations segment of the affordability picture. Preliminary results are provided here for some example launch systems and launch ranges. More detailed analysis of launch range capabilities and payload varieties is on-going. Interestingly, the spacelift metric incorporates dependability in that failed launches do not accrue in the metric (e.g., the rise in performance between 1987 and 1990 reflects the downtime recovery of U.S. systems due to the catastrophic failures in the late 1980s).

<u>Example Spacelift Performance Comparisons</u>

The first comparison of spacelift performance will be on a launch site-by-launch site basis. An example for United States launches is provided in Figure 1.[2]

The predominant contribution of the spacelift performance can be seen in Figure 2, where the Space Shuttle system averages about 15 metric tons (MT), or about 33,000 pounds, per flight at an average of seven or eight flights per year.

To see an example from the ground system viewpoint, he breakdown of the same spacelift performance by launch facility can be seen in Figure 3. It can be observed in the graph that the pad facilities often rotate carrying the spacelift load and undergo periodic "downtime" to rejuvenate the launch facility systems. Likewise, in Figure 4, reusable flight assets (e.g., the Space Shuttle Orbiter vehicles) can be seen undergoing the same periodic "downtime" for inspections, modifications, and overhaul maintenance.



<u>FIGURE 2</u>—U. S. Spacelift Performance by Launch System (1987-1997)

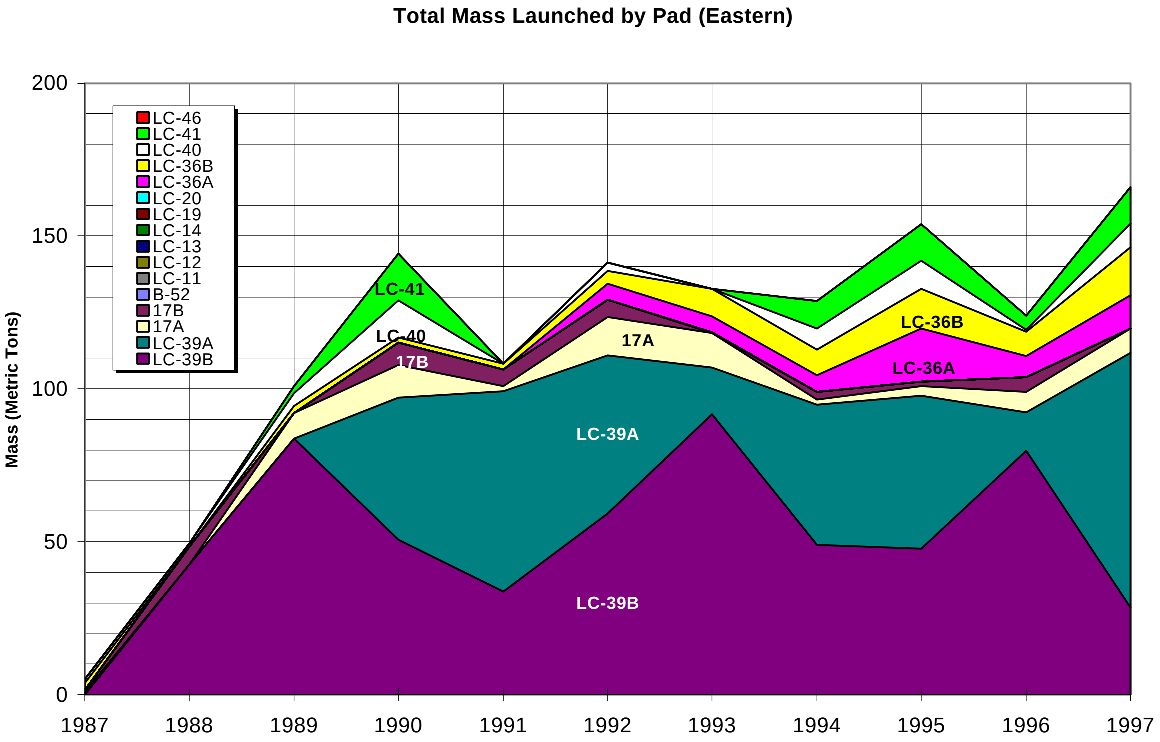


FIGURE 3—U. S. Spacelift Performance by Launch Facility (1987-1997)

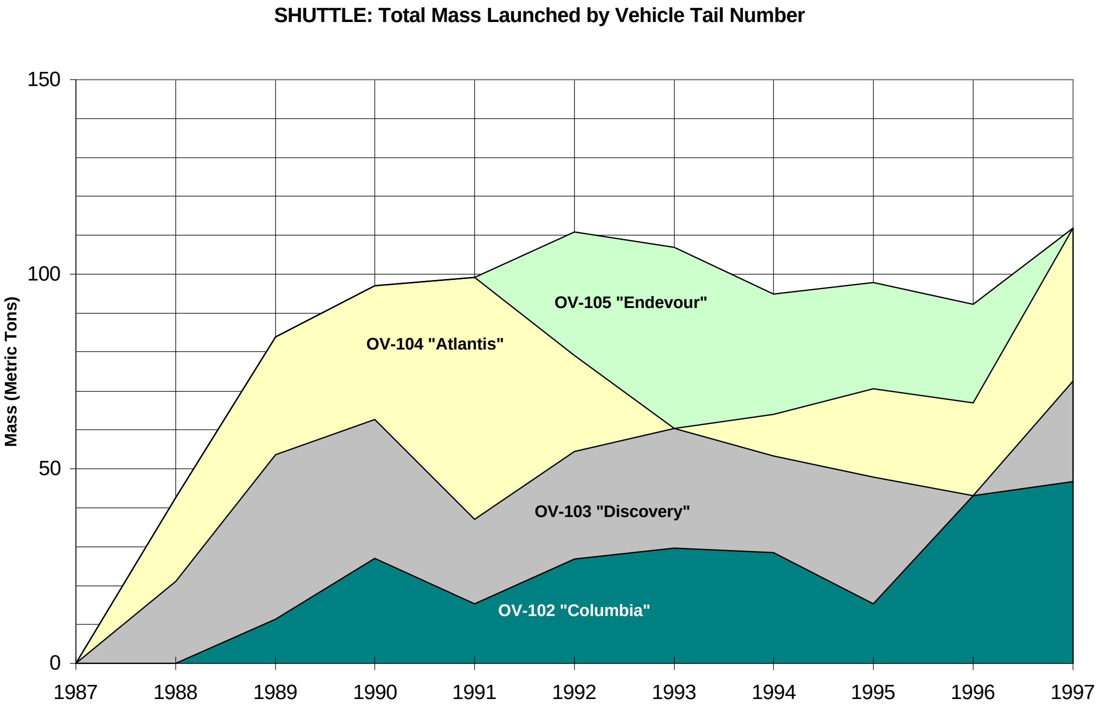


FIGURE 4—Space Shuttle Fleet Spacelift Performance (1987-1997)

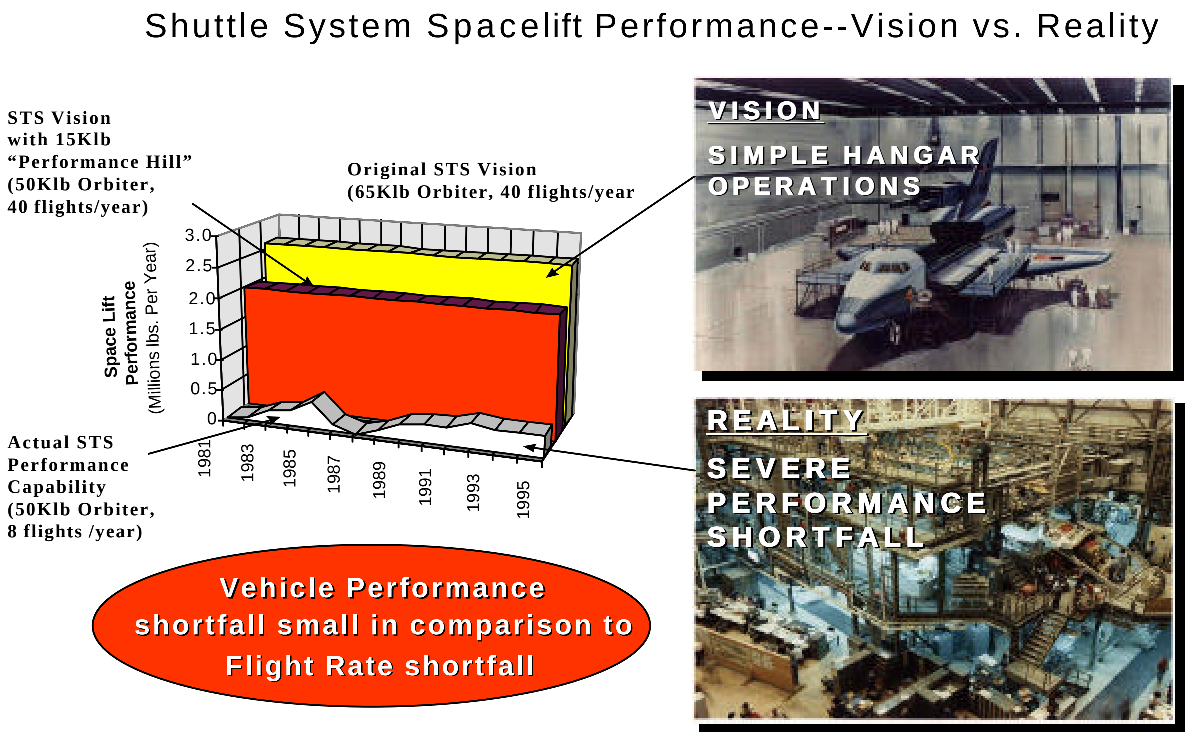


FIGURE 5—Eliminating complex flight-to-ground interactions & resulting infrastructure is key to improving spacelift

While the results are still in preliminary form, the primary point to be observed is that the performance of a space transportation system does not depend entirely on in-flight performance. Such factors as flight rate and the dependability of the launch systems (flight and ground) are important in maximizing the performance of competitive launch services. Affordability is also of utmost importance in today's competitive launch services environment. It is left to the reader to use benchmarking data, such as that presented here, to derive annualized cost and price-per-kilogram information.

IS TODAY'S SPACELIFT PERFORMANCE CAPABILITY ACCEPTABLE?

Today's space launch environment has several near-term requirements. Launch services can satisfy the needs of commercial enterprises, civil and scientific exploration missions, and military missions. The example benchmarks of spacelift performance noted in figures 1-3 indicate a slight increase in overall spacelift performance—but will this be enough to satisfy the needs for envisioned commercial enterprises, future exploration missions and for maintaining global peace and security?

Spacelift Performance Lessons from Shuttle

As large as the Shuttle contribution is to today's spacelift capability, experience gained in the development and subsequent operation of the system should provide us insight on how to design greater spacelift performance during early conceptual design.

Figure 5 shows a history of spacelift capability for the Space Shuttle from conceptual design through actual operation. The original concept of Orbiter turnaround maintenance operations, for example, envisioned a simple vehicle to operate and maintain with an expected flight rate of forty per year. There would be little infrastructure to service, inspect and checkout the vehicle. Additionally, payload integration would be simple, implying very little labor. The illustration of the "vision" of operations above was rendered circa 1974, prior to detailed systems definition. By the time the Shuttle architecture (flight and ground) was in operation, the complexity of the ground infrastructure had grown to meet the servicing, inspection and checkout required by the vehicle design. As a result, the expectation of spacelift performance (the top line in the graph and a product of the flight rate times the single mission lift capability) versus its actual performance (the lowest area in the graph) can be seen in Figure 5. A stable flight rate of about eight per year for a fleet of four vehicles had been achieved through 1997. Likewise, the single mission lift capability had not met expectation, dropping from the original 30 MT (65,000 lbs) concept to 23 MT (50,000 lbs) actually fielded for operation. However, had the original operations concept been fielded, with its expected flight rate of forty per year, while still suffering in single mission lift performance, i.e., 23 MT (50,000 lbs), the spacelift impact would not have been nearly so severe (the middle area in the Figure 5 chart). Lesson that should be learned: the vehicle performance shortfall was small compared to the flight rate shortfall, and this had tremendous implications on spacelift performance of the total Shuttle system architecture—flight and ground.

Single Vehicle Flight Rate Capability

One important design parameter that should be examined and estimated throughout the life cycle of a concept is the 'single-vehicle' capability. The current Shuttle Orbiter spacelift capability (as exemplified in Figure 4) is approximately two to four flights per year per vehicle, or about 30-60 metric tons per year per vehicle. Such a metric defines a 'single-vehicle' flight rate or spacelift capability and has become a focus of recent NASA studies for long-term concept and technology planning.

The single vehicle flight rate capability requires special attention during conceptual design. For it is during the conceptual design phase that the first opportunity for establishing the order-of-magnitude of required ground infrastructure is established. The order-of-magnitude of cycle time to turnaround the vehicle, or otherwise produce a flight, is also established. Propulsion system specifications for propellant type, arrangement of tank and flight structures that can create requirements for added pogo-suppression systems, thermal protection types, complexity of the flight control systems, etc.—all have tremendous impact on the level of infrastructure on the ground and the resulting responsiveness of the ground flight production process. Likewise, the concept for creating a dependable transportation system, that not only insures flight safety, but insures unplanned maintenance levels are kept to near zero, have a tremendous effect on the operational flight rate. The concept's lift performance per flight combined with its attributes of responsiveness and dependability will ultimately define its spacelift performance capability.

For the near-term, perhaps today's rate of space launch production will meet upcoming commercial growth needs. The single vehicle flight rate capability of the Space Shuttle should also meet the deployment and initial operations of the International Space Station (ISS). However, looking at future spacelift requirements, it is becoming more and more evident that radically new launch concepts, far simpler in their support requirements and far more dependable, will be required if such enterprises as space solar power or public space travel are to become reality.

Space Solar Power: Example Spacelift Requirement

NASA is currently examining with industry and academia the business, economic and technical requirements for deploying space solar power systems that might one day collect solar energy in space and beam the converted energy to earth. The requirements are being examined in the context of two particular systems concepts (Figures 6 and 7), (1) a set of massive geo-synchronous earth orbit (GEO) "Solar Dishes" in one concept, and (2) a system of low earth orbit (LEO) "Sun Towers" (massive enough in their own right).

The study constrains the cost for transportation to LEO to $400 per kilogram in order to support a space solar power system baseload cost of 5¢ per kilowatt-hour. For the two space solar power configurations, and given a thirty year deployment period for each scenario, the preliminary spacelift requirements have been reduced by Dr. John Olds of Georgia Tech to the following:[3]

LEO Sun Tower Architecture (30 @ 1/year)

- Initial flight rate~250 per year
- Peak flight rate~300 per year
- ~8,400 flights (30 year deployment period)
- ~160,000 metric tons to LEO (30 year deployment period)

Solar Disk Architecture (6 @ 0.2/year)

- Initial flight rate~420 per year
- Peak flight rate~500 per year
- ~13,000 flights (30 yr. deployment period)
- ~248,000 metric tons to LEO (30 year deployment period)

Sun Tower Data

Mass/each	4,850 MT[†]
Orbits (km):	
Delivery	300 @ 28.5° or 0°
Assembly	1,200 @ 0°
Operational	12,000 @ 0°
Dimensions/each	15 km (height)
Power on Ground	400 MW

† - VRC/SSP wing document SAIC-1, 06/01/98

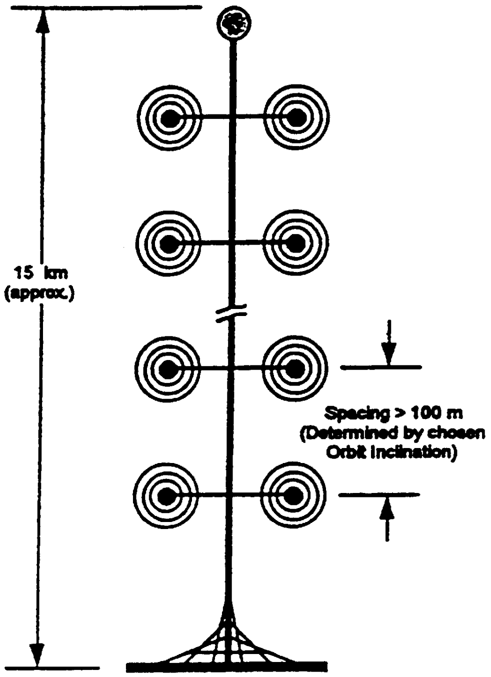
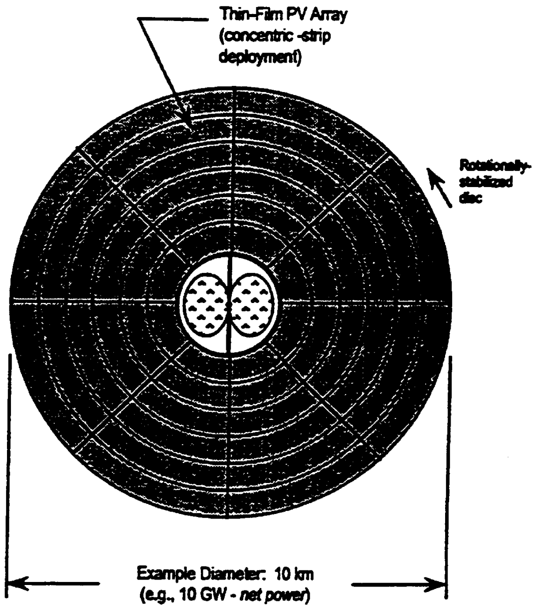


FIGURE 6—*'Solar Tower'* Configuration, NASA Space Solar Power Spacelift Reference



Solar Disk Data

Mass/each	40,000 MT
Orbits (km):	
Delivery	300 @ 28.5°or 0°
Assembly	1,200 @ 0°
Operational	35,860 @ 0° (GEO)
Dimensions/each	10 km (diameter)
Power on Ground	5,000 MW

FIGURE 7—*'Solar Disk'* Configuration, NASA Space Solar Power Spacelift Reference

These aggressive spacelift requirements, coupled with aggressive affordability, and responsiveness requirements are being jointly pursued by Georgia Tech and the Kennedy Space Center for NASA’s Marshall Space Flight Center, in an effort to uncover radically new flight and ground space transportation architectures.

Public Space Travel

Another visionary spacelift requirement will be public space travel. This type of market will, of necessity, require orders-of-magnitude increases in safety and dependability of the flight and ground systems. The Space Shuttle has thus far demonstrated about ninety flights with one catastrophic failure, i.e., a demonstrated reliability of 0.989. While acceptable for the current infrequent launch of scientists and flight crew, such a level of dependability will hardly suffice for frequent public travel. Each Shuttle Orbiter vehicle, for example, is designed for 100 mission use. Given the level of dependability achieved in the Shuttle Orbiter, about 50-100 line replaceable units (LRU’s) are required to be removed and replaced between each flight due to a failure found a) in flight, b) on the line or c) while under test or inspection (10%, 55%, and 35%, respectively, according to a recent analysis).

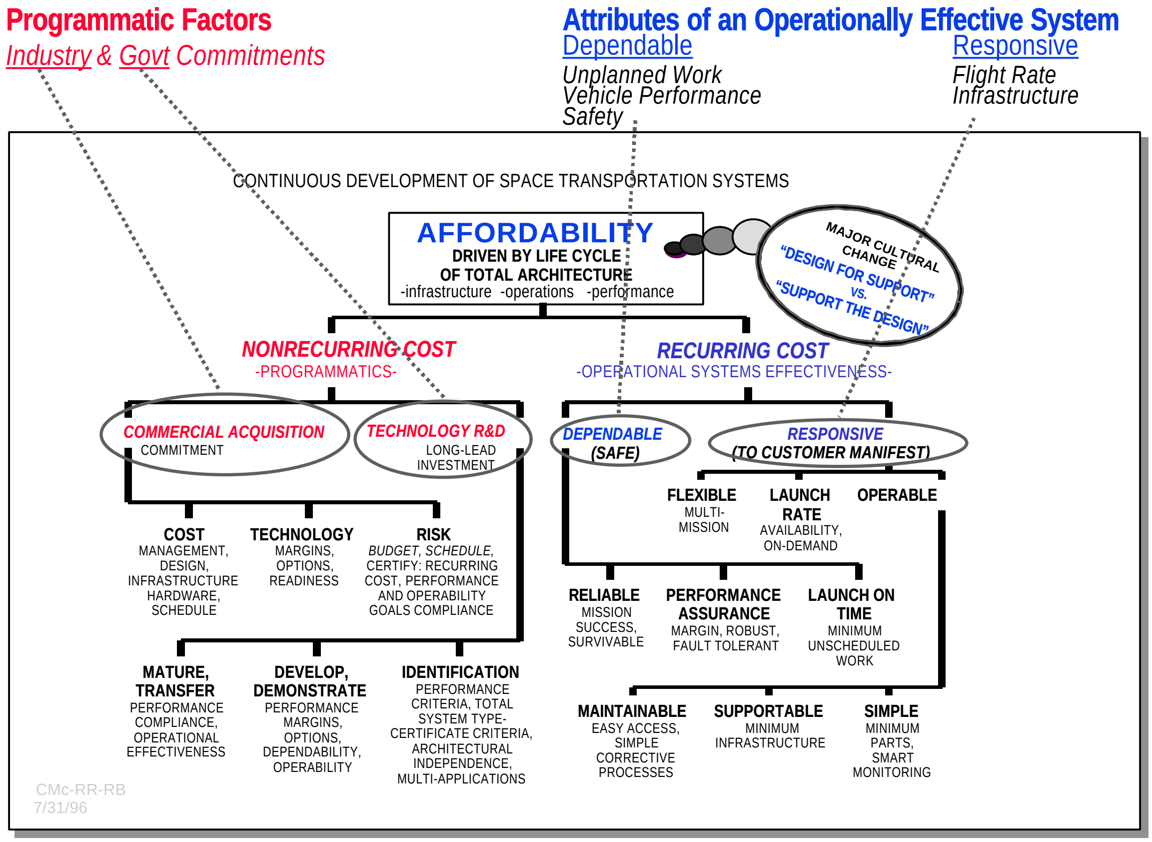


FIGURE 8—Mapping space launch affordability throughout the life cycle

ATTRIBUTES & DESIGN CHARACTERISTICS OF HIGHLY CAPABLE SPACELIFT SYSTEMS

Since the interaction between the flight and ground systems is an important design aspect to consider, recent efforts by the Space Propulsion Synergy Team (SPST) and sponsored by NASA and American Institute of Aeronautics & Astronautics (AIAA) have begun to prioritize specific design feature improvements according to the attributes of affordability, responsiveness and dependability. A method was employed that not only prioritized the benefit of improving various design features, but also organized “programmatic” factors. These programmatic factors include prioritized risks and level of technical maturity and, therefore, provides insight into a launch system’s life cycle cost factors (up-front costs by assessing the programmatic factors and operating costs by assessing the benefit). A mental map of these attributes throughout the life cycle are shown in Figure 8.

A CATALOG OF SPACEPORT FUNCTIONS

Having a prioritized set of design features has been useful for making qualitative assessments that surface operationally effective concepts and technologies. Still, a more quantifiable means of determining ground system contributions to life cycle costs is needed. Anticipating this need, the SPST and the NASA HRST study manager recommended that KSC formulate a "generic spaceport model" that would be capable of both quantifying the ground contributions to life cycle cost while capturing the design knowledge of launch site technologists. What emerged was the *Spaceport Catalog*.[4] It's intent was to define a highly productive operational spaceport in a generic sense. A catalog of generic spaceport ground system functions was created and organized into twelve generic functional "modules". These modules do not necessarily equate to a singular facility, nor does every concept require all the modules or all functions within the modules. In fact, the objective would be to create a flight system concept that required as few of the functions as possible, perhaps to the point of eliminating entire modules from the architecture. The *Spaceport Catalog* was, therefore, created with a vision towards one day defining a highly efficient spaceport architecture operating highly effective (and profitable!) flight systems. The twelve possible modules include:

1-Payload/Cargo Processing Facilities

2-Traffic/Flight Control Facilities

3-Launch Facilities

4-Landing/Recovery Facilities

5-Vehicle Turnaround Facilities

6-Vehicle Assembly/Integration Facilities

7-Vehicle Depot Maintenance Facilities

8-Spaceport Support Infrastructure Facilities

9-Concept-Unique Logistics Facilities

10-Transportation System Operations Planning & Management Facilities

11-Expendable Element Facilities

12-Community Infrastructure

DESIGNING FOR ANNUAL SPACELIFT PERFORMANCE

As an outcome of NASA's Highly Reusable Space Transportation (HRST) Study, a growing set of design principles are emerging and are being documented. Some of these are listed below:

A. Reduce the overall number of fluids, do not use toxic fluids

B. Integrate propulsion system components

C. Use reliable, commercial-off-the-shelf products that are produced in high quantities

D. Automate checkouts of systems and turnaround facilities

E. Design for accessibility without requiring special equipment

F. Minimize interfaces between flight and ground systems

G. In Summary: Integrate; Eliminate; Automate; and Design in Maintainability, Reliability, and Margin

VISION SPACEPORT PROJECT

Currently, NASA's John F. Kennedy Space Center is engaged in a Joint Sponsored Research Agreement (JSRA) with several industrial and small business partners to begin producing the benchmarks, the tools and a vision for modeling space launch systems and their spaceports of the future. The effort includes building a database of global spacelift performance, building a strategic decision-making software modeling tool for use during space launch system conceptual design, as well as creating some "templates" for this model that includes both existing and advanced concepts.

The long-term objective of the project is to develop technical means for conducting concept work, preliminary design and perhaps even detailed design. Until such means are successfully developed, it will remain a difficult task to design for affordable annual spacelift performance.

ACRONYMS

AIAA—American Institute of Aeronautics and Astronautics
CCAS—Cape Canaveral Air Station
EAFB—Edwards Air Force Base
GEO—geosynchronous earth orbit
HRST—Highly Reusable Space Transportation
ISS—International Space Station
JSRA—Joint Sponsored Research Agreement
KSC—Kennedy Space Center

lbs.—pounds
LC—Launch Complex
LEO—low earth orbit
MT—metric ton
NASA—National Aeronautics and Space Administration
SPST—Space Propulsion Synergy Team
STS—Space Transportation System
WFF—Wallops Flight Facility

REFERENCES

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[1] Guide for the Design of Highly Reusable Space Transportation, Space Propulsion Synergy Team (SPST), August 29, 1997.

[2] NASA KSC, Lockheed Martin and Boeing; NASA Joint Sponsored Research Agreement (NCC10-0030), Task 2.0; August, 1998.

[3] Space Solar Power Briefing, Dr. John Olds, Georgia Tech, 1998.

[4] A Catalog of Spaceport Architectural Elements, SPST, 1998.