IAF-99-R.3.02

Spaceport Operations Assessment for Space Solar Power Earth to Orbit Transportation Requirements

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ABSTRACT

This paper presents a spaceport-focused operations assessment within the context of Earth to orbit (ETO) transportation requirements to support a major Space Solar Power (SSP) satellite deployment initiative. These requirements include the delivery of over 15,000 metric tons to orbit per year at *prices* to the SSP system developer of only $400/kg (approx. $181 per pound). The highly reusable space transportation systems optimized around this overriding objective will be described. This process of optimization has included not only the flight vehicles, but just as importantly, the interaction of a flight system with its ground infrastructure (the spaceport). Modeled interactions included the flight vehicle's facilities and ground support equipment requirements and costs resulting from ground operations (processing labor, replacement hardware items, propellants, etc.). Key outputs from the spaceport model included vehicle ground processing time and resultant impacts on overall fleet size.

The process of optimizing these systems and the resulting implications to costs of factors such as reliability, life and margin, and complexity, will also be explained. The model used to predict the effect of designs on ground systems and the resulting costs will be reviewed. It will be shown that investments in infrastructure as well as flight systems will be necessary to meet the SSP price goal of $400/kg.

INTRODUCTION

From 1995 through 1998, NASA conducted a reexamination of the concept of Space Solar Power. The principal objective of this fresh look study was to:

> "determine whether a solar power satellite and associated systems could be defined that could deliver energy into terrestrial electrical power grids at prices equal to or below ground alternatives in a variety of markets, do so without major environmental drawbacks, and which could be developed at a fraction of the initial investment projected for the reference System of the late 1970s."[1]

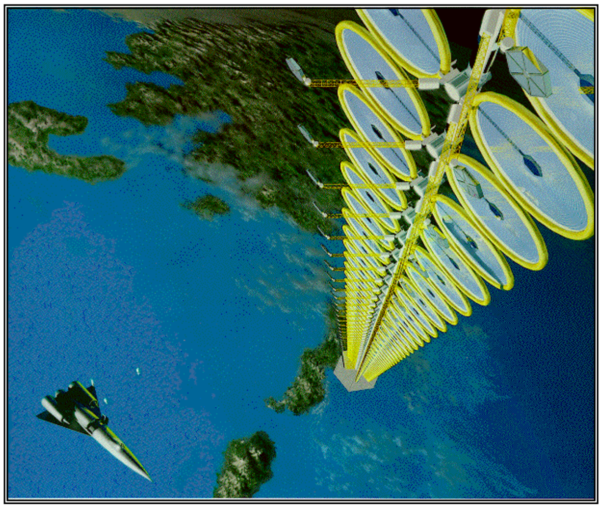


FIGURE 1. SSP Suntower and ETO Vehicle.

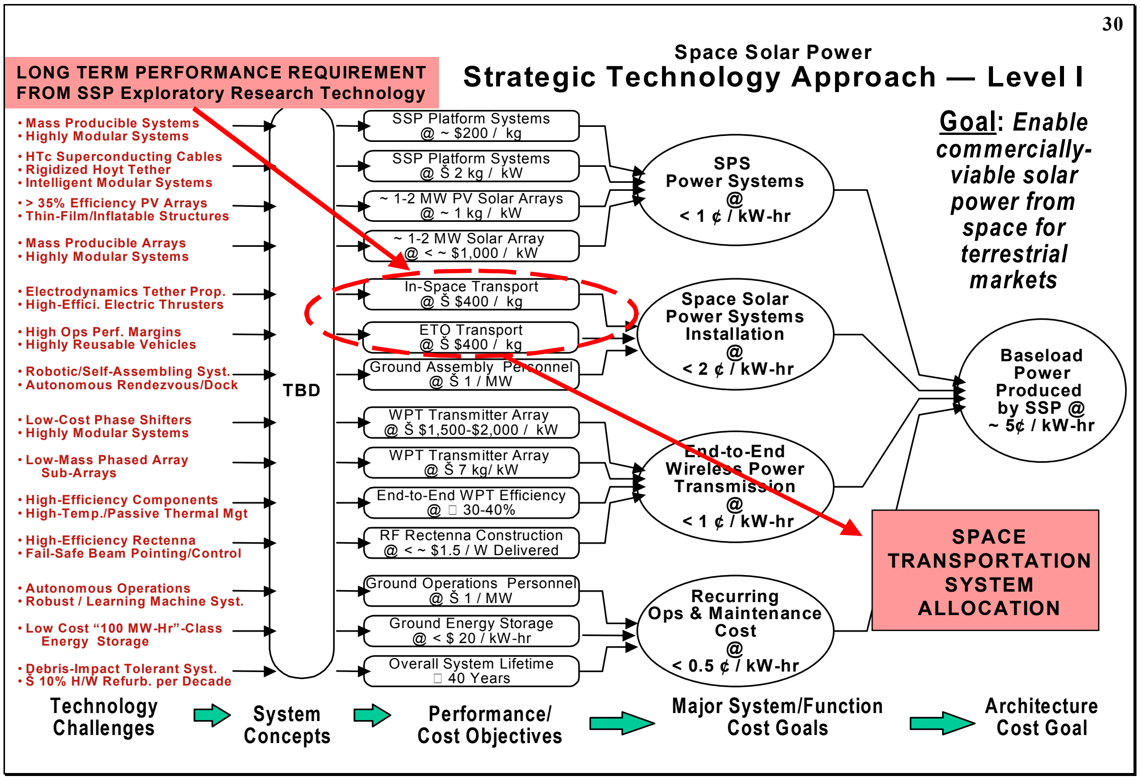


FIGURE 2.0. SSP reverse allocation of requirements, including the space transportation system.

Such a system is envisioned in Figure 1.0 (the Suntower). The requirement that the new concept have a “fraction of the initial investment” of the 1970’s reference SSP system is a recognition of the significance that ETO costs have on the overall economics of SSP. That is, transportation costs (ETO and in-space transfer vehicles) are a major contributor to the overall life cycle cost of SSP. An economic rollup of contributing costs for an economically successful SSP venture is given in Figure 2.0. In order to meet a power delivery price of approximately 5 U.S. cents per KW-hr, the purchase *price* for ETO delivery services must be no more than $400/kg of payload. This aggressive target represents a factor of 20 reduction over today’s ETO launch prices.

A joint NASA-university study team was formed to investigate ETO launch vehicle options for meeting the $400/kg price goal for SSP. The question to answer was:

> “Is it feasible to create ETO transportation systems, within the next generation, that can meet mass delivery and price requirements of SSP, while still returning an acceptable economic return to the launch vehicle developer/operator?”

Table 1 gives the annual SSP mass requirements used for the current study. The resultant annual flight rates for two different launch vehicle payload capabilities (20 MT per flight and 40 MT per flight) are also given. Note that initial vehicle studies considered vehicles capable of delivering 20 MT payloads to LEO. The final configurations selected were capable of delivering 40 MT per flight. The high annual flight rate requirements dictate that candidate vehicles have a high responsiveness, high reliability, and high availability (“almost” airline/airport-like). Limited fleet sizes and spaceport infrastructure will also be required, as vehicle and spaceport non-recurring acquisitions eventually flowdown to recurring costs (primarily via payback of debt). The aggressive *price* goal of < $400/kg places a requirement on the ETO operator that direct *costs* must be less than about $200/kg to allow recovery of non-recurring

TABLE 1.0 ETO Requirements for SSP.

SSP Tower	Transportation System Requirement
SSP Deployment Rate	3 Suntowers per year
Mass Delivered	~15,561 MT per year
Delivery Price	< $400/kg
ETO Flight Rates	If 20MT vehicle payload: ~780 flights / year minimum If 40 MT vehicle payload ~ 390 flights / year minimum

costs and produce acceptable rates of return on investment[3]. Note that modeling payload packaging inefficiency will actually increase annual flight rates above the already high "minimums" shown in Table 1.0.

THE CONCORDE COMPARISON

As a rather useful point of departure, the operation of an aircraft system such as the Concorde bears some similarity to the type of operations that might be required of an ETO spaceline fleet supporting an SSP customer. Some useful Concorde metrics for benchmark purposes are shown in Table 2.0. Note that the estimated price for a Concorde flight on a simple mass basis is $76/kg.

For making a better distinction recall that the SSP ETO challenge is to have a price of less than $400/kg of payload (<$200/kg in direct costs). This price is not far removed from the Concorde revenue (price) of $76/kg, especially considering:

- Concorde development and vehicle acquisitions were absorbed by the British and French governments allowing the airline operators to have reduced operating costs. Payback of non-recurring costs are not a part of Concorde operations. If the SSP vehicle did not have to recover most of its up front investment costs (fleet acquisition), its direct cost and price could be closer together (i.e. price closer to $250 - $300/kg).

- A trip distance more analogous to that of an ETO vehicle (at least as far as "round the world"[4]) could be 4 to 5 times the base Concorde price in Table 2.0. This would be in the same range as the price targeted for the SSP ETO systems.

TABLE 2.0 Concorde measures for comparison.

Concorde[2]
• Size of fleet = 14 (British Airways 7, Air France 7)
• Cost per flight, New York to London ~ $10,000 (U.S. dollars) per passenger
• Number of passengers = 100
• Maximum payload ~ 13.2 MT (29,000 lbs)
• Dry weight ~ 92.2 MT (203,000 lbs)
• Revenue/flight ~ $1M
• Revenue/kg = ~ $76/kg ($34/lb), this is a <u>price</u>, not cost
• Average flights per year per vehicle since first flight ~ 250 (G-BOAA, s/n 206, first flight Nov. 75, counting only supersonic cycles, actual landings slightly higher)

PREVIOUS WORK – THE HRST STUDY

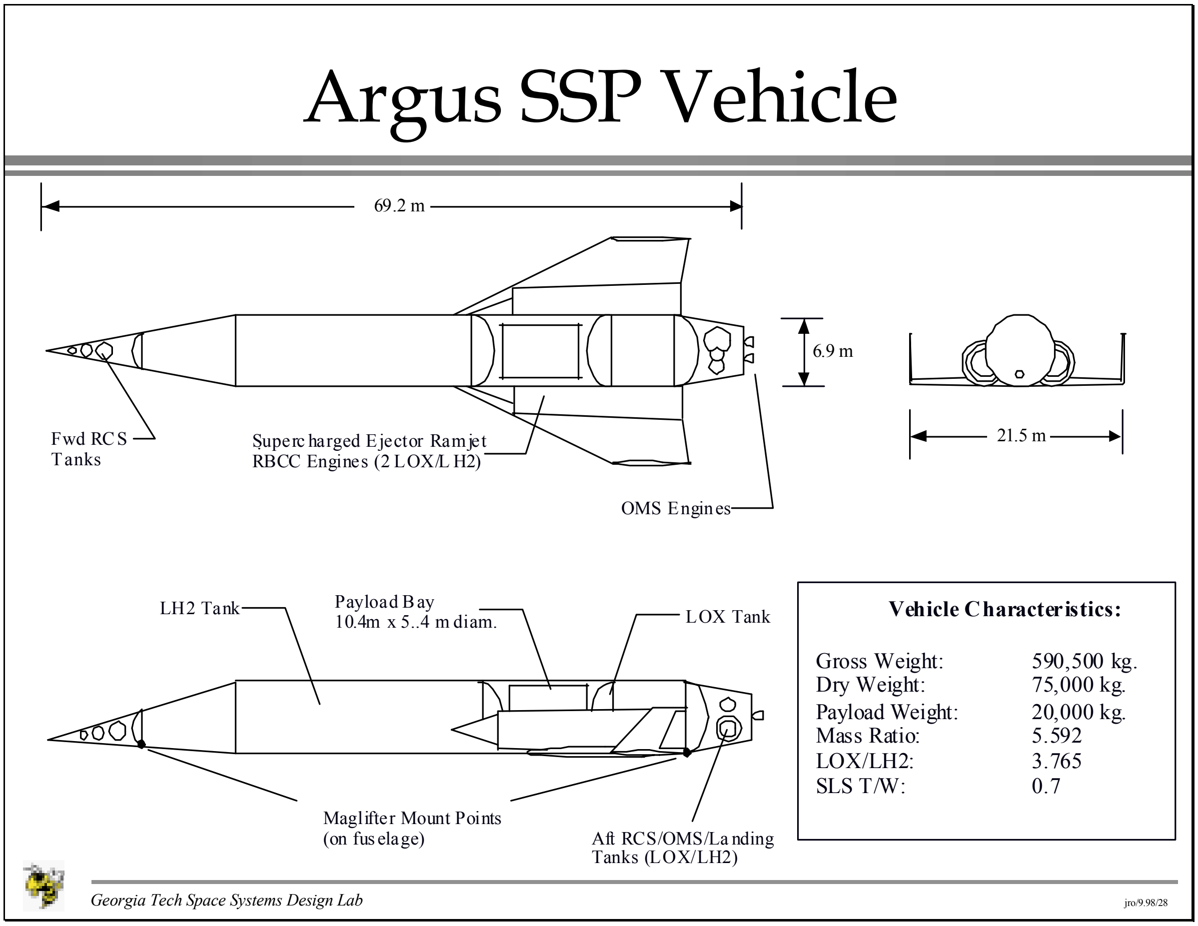
In late 1998, NASA completed the Highly Reusable Space Transportation (HRST) system study. Its goals were similar to the requirements later synergistic with SSP needs. The study objective was the definition of reusable space transportation systems, concepts and technologies capable of achieving a two order of magnitude reduction in direct launch costs relative to today's expendable launch vehicles. Approximately 20 concepts were examined in the 20 MT – 40 MT payload range. The study concluded that rocket-based combined-cycle (RBCC) approaches “offer significant near term potential toward achieving HRST objectives of cheap access to space at [costs of] \$100 to \$200/lb of payload[5]”. These concepts set the stage for further refinement in light of the specific needs of Space Solar Power satellite deployment.

MODELING FOR OPERATIONS

Advanced simulation and modeling is required to consistently, traceably and confidently predict operations costs for future ETO systems. This modeling should combine not only data but expert knowledge in an iterative process of evolving the ETO concepts and technologies based on operational, performance, and economic requirements. Derived from work undertaken on the HRST study, a model was employed that:

- Utilizes only a conceptual-level of systems definition to avoid requiring highly detailed subsystem data from vehicle designers
- Includes comprehensive cost breakdowns so as not to neglect “hidden costs”
- Generates maximum expected annual flight rate capability for a single airframe to allow analysts to predict overall fleet size required to meet a given mission model

This new model is called the Architectural Assessment Tool – enhanced (AATe)©[6].

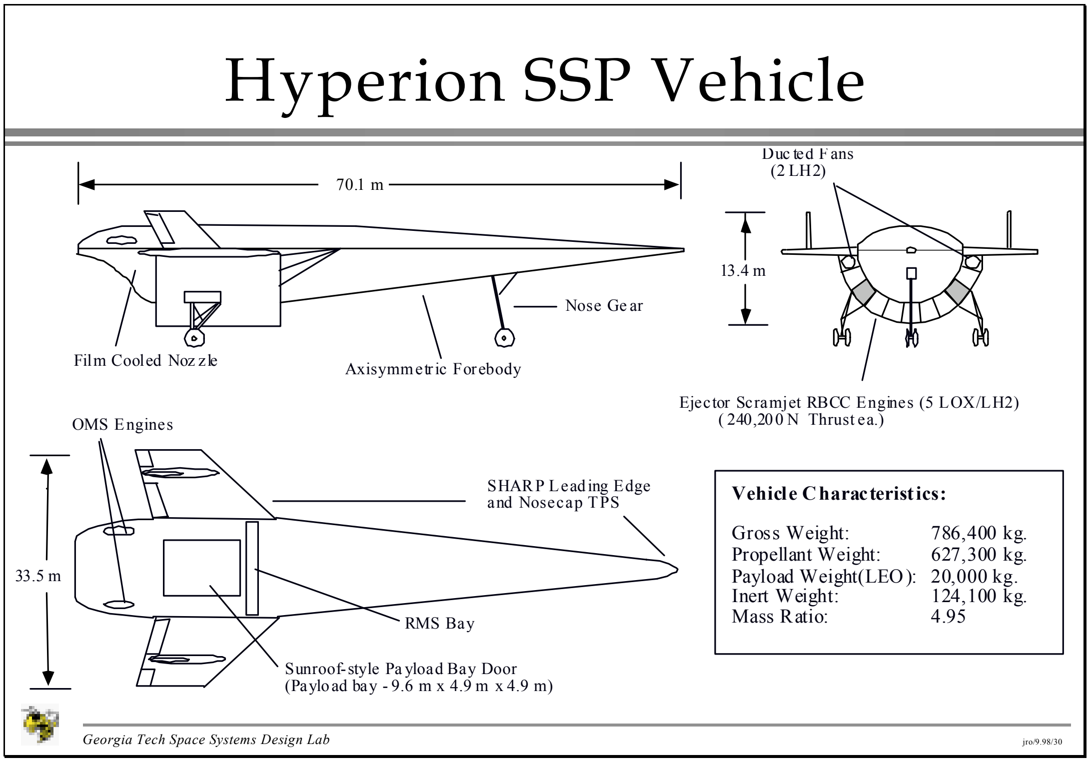


Argus SSP Vehicle

Vehicle Characteristics:

Gross Weight:	590,500 kg.
Dry Weight:	75,000 kg.
Payload Weight:	20,000 kg.
Mass Ratio:	5.592
LOX/LH2:	3.765
SLS T/W:	0.7

FIGURE 3.0 The *Argus* RBCC SSTO concept, launch assisted with Magnetic Levitation System & Sled. A super-charged (with fan) ejector ramjet with a (relatively) low Mach transition number of 6 to all-rocket mode.



Hyperion SSP Vehicle

Vehicle Characteristics:

Gross Weight:	786,400 kg.
Propellant Weight:	627,300 kg.
Payload Weight(LEO):	20,000 kg.
Inert Weight:	124,100 kg.
Mass Ratio:	4.95

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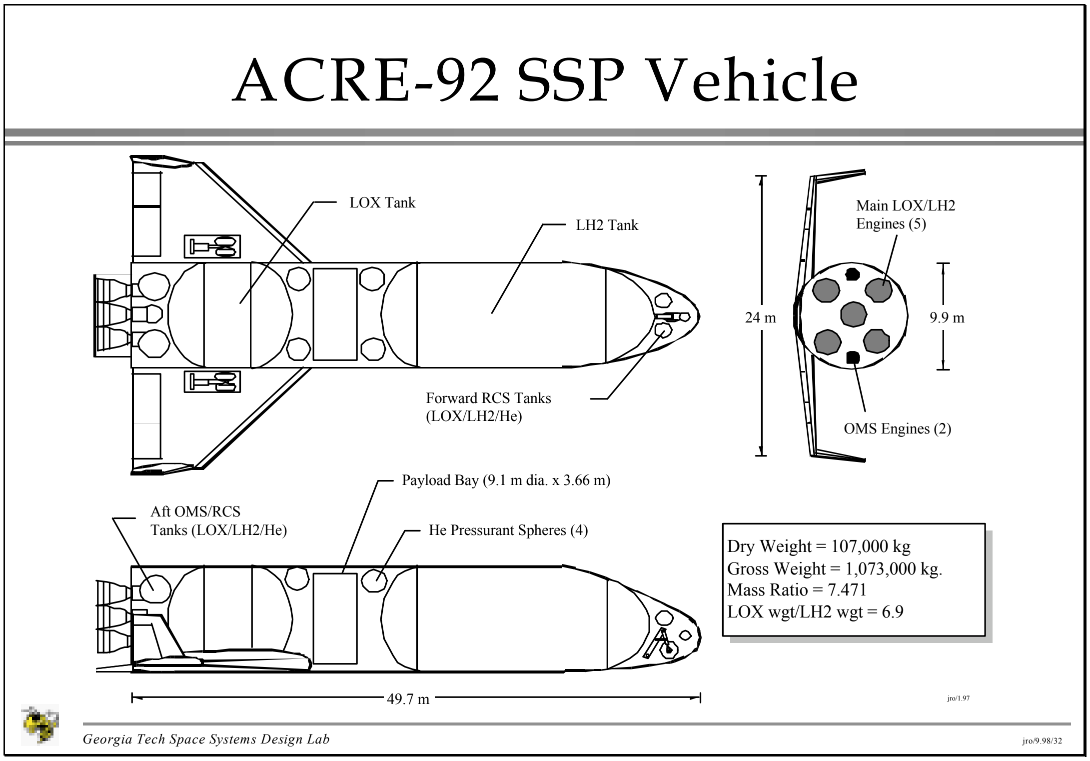
FIGURE 4.0 The *Hyperion* concept, a horizontal take-off RBCC SSTO concept, with a Mach 10 (scramjet) transition to all-rocket mode. Loiter capability on return given by the addition of ducted fan engines.



ACRE-92 SSP Vehicle

Dry Weight = 107,000 kg
Gross Weight = 1,073,000 kg.
Mass Ratio = 7.471
LOX wgt/LH2 wgt = 6.9

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FIGURE 5.0 The ACRE-92 concept, a vertical take-off rocket SSTO utilizing 5 advanced LOX/LH2 rocket engines with a high (92:1) thrust-to-weight ratio.

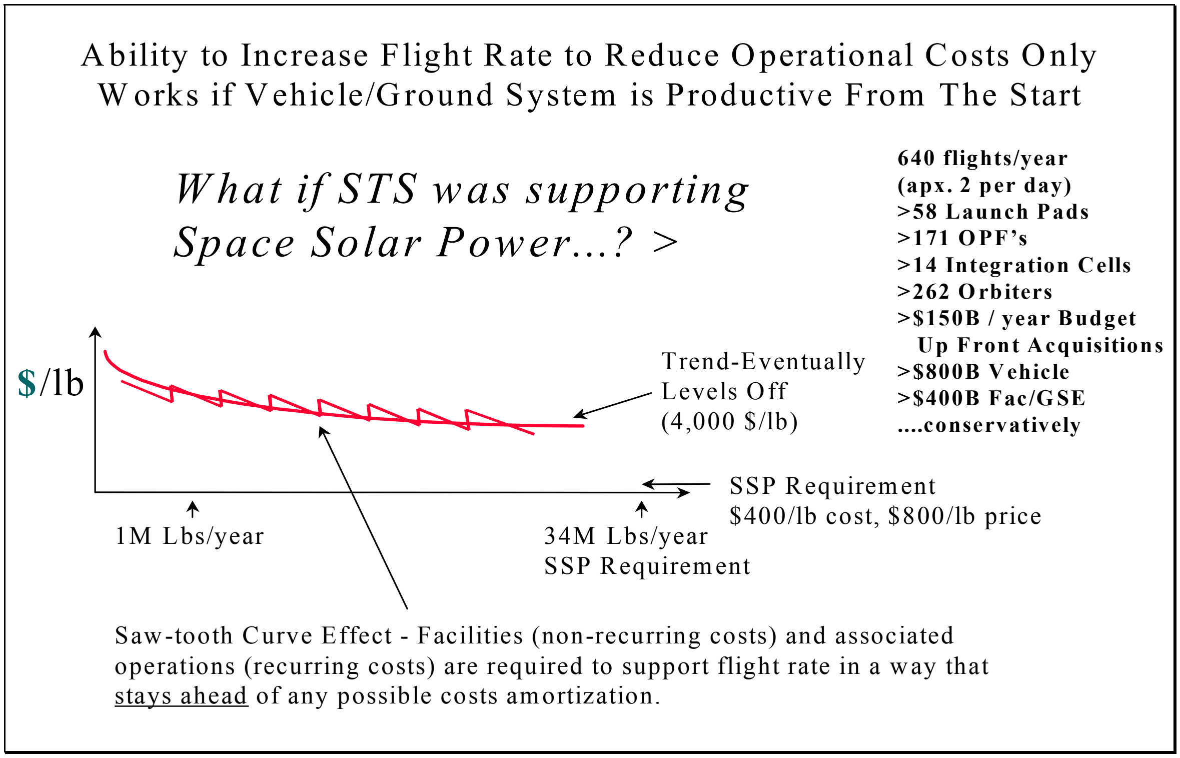


FIGURE 6.0 What if the Shuttle supported SSP?

Three early vehicle concepts were considered for the current SSP mission, based on being the most promising from the HRST study. These candidate concepts include an advanced single stage rocket and two RBCC airbreather concepts. The initial 20 MT payload versions are shown schematically in Figures 3.0, 4.0, and 5.0.

Other concepts not included here, such as a horizontal take-off rocket SSTO with low speed launch assist, have some similar features as those shown previously. Note that the initial SSP concepts were designed to deliver 20 MT payloads to a 300 km circular orbit. Subsequent SSP design studies suggested that 40 MT payloads might even be more economically attractive! These are not small payloads. For comparison, the U.S. Space Shuttle is capable of delivering about 25 MT to LEO.

SHUTTLE AS REFERENCE

For a relative understanding of the challenge at hand, and of what would be the implications for costs, an assessment is included here with Shuttle as cargo delivery for SSP.

Assuming:

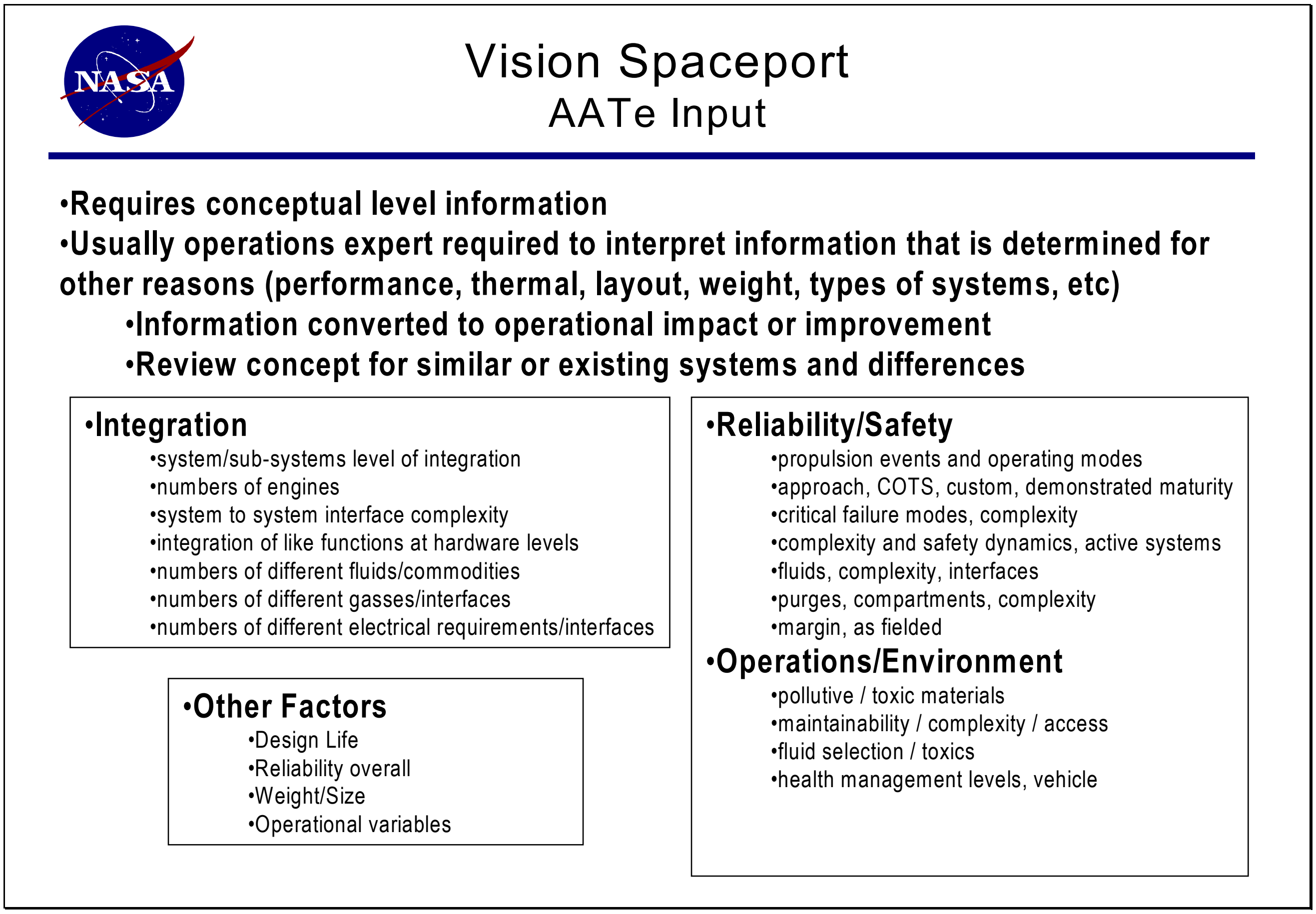
- No changes in basic design of orbiters or facilities.
- Holding the SSP flight rate and payload capability as a fixed requirement and calculating the resultant operating cost

Figure 6.0 details the implications of such an approach. The "saw-tooth effect", the effect of adding ground facilities (costs) incrementally to keep ahead of demand, would also be apparent for any new concepts that could conceivably support SSP on flight rate, payload, AND costs. The growth of facilities is not per se limited for SSP ETO concepts. In so far as concepts can achieve fast turnarounds with little manpower costs, new facilities, even into the $1B to 3B range, could be amortized over the life of the vehicles and over every customer payable flight.

ASSESSMENT PROCESS

The original concepts as proposed required improvement in order to begin to meet SSP goals. Early HRST assessments ranged from 10 to 20 flights per year per vehicle for such concepts as *Argus*, ACRE and *Hyperion*. This single vehicle flight rate translates to a calendar time of about one month to two weeks between launches of a given airframe. For a representative flight rate of 500 flights per year for the entire fleet, a fleet size of 25 – 50 vehicles would be required to accomplish the SSP deployment mission. This large fleet leads to prohibitive non-recurring costs and a poor overall economic performance for the RLV developer[3]. Clearly a better vehicle utilization rate was needed in order to meet the goal of $400/kg price and still make money for the RLV developer.

An iterative process between vehicle designers at Georgia Tech and ground operations experts at Kennedy Space Center was used to identify promising areas of possible improvement in the vehicle designs. The iterative design process considered factors as shown in Figure 7.0. The AATe© tool was a valuable aid in assessing expected operations gains from various design changes.



Vision Spaceport
AATe Input

- **Requires conceptual level information**
- **Usually operations expert required to interpret information that is determined for other reasons (performance, thermal, layout, weight, types of systems, etc)**
  - **Information converted to operational impact or improvement**
  - **Review concept for similar or existing systems and differences**

•Integration
- system/sub-systems level of integration
- numbers of engines
- system to system interface complexity
- integration of like functions at hardware levels
- numbers of different fluids/commodities
- numbers of different gasses/interfaces
- numbers of different electrical requirements/interfaces

•Other Factors
- Design Life
- Reliability overall
- Weight/Size
- Operational variables

•Reliability/Safety
- propulsion events and operating modes
- approach, COTS, custom, demonstrated maturity
- critical failure modes, complexity
- complexity and safety dynamics, active systems
- fluids, complexity, interfaces
- purges, compartments, complexity
- margin, as fielded

•Operations/Environment
- pollutive / toxic materials
- maintainability / complexity / access
- fluid selection / toxics
- health management levels, vehicle

FIGURE 7.0 Factors considered in improving a conceptual space transportation systems operations, including non-recurring operations impacts such as one-time, non-recurring costs of facilities and GSE as well as recurring operations costs, such as labor and materials. INTEGRATION, RELIABILITY / SAFETY, & OPERATIONS / ENVIRONMENT groups, as well as other factors such as life, weight and size, and operational variables.

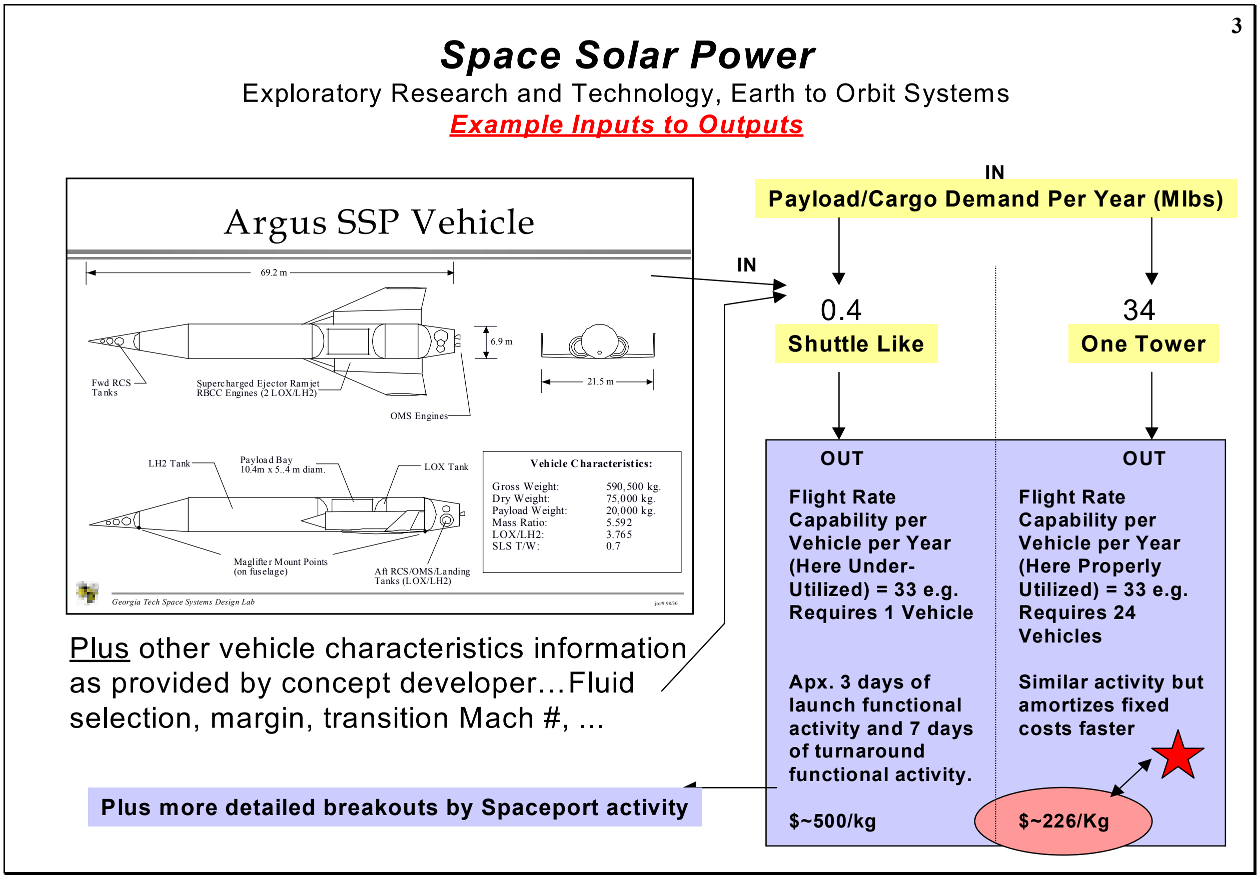
Key changes were made to the vehicle designs via the addition of "robustness" margin on primary structural components (reducing inspection time), derating engine performance to 90% of nominal (extending engine life), and using commercial-of-the-shelf (COTS) actuators and subsystems (reducing inventory costs). Main propulsion system functions were combined where possible. Non-common fluids were eliminated. On *Hyperion*, loiter engine count was reduced and forebody purges were eliminated.

OPERATIONS ASSESSMENTS

An operational assessment of the vehicles considered here would proceed as shown in Figure 8.0. Key design features that bear indirectly on operational factors such as cost or cycle times include, among others:

- Numbers and layout of engines?
- Numbers and layout of tanks?
- Thermal Protection System (TPS) assessment?
- Is active cooling required on the airframe?
- What is the maximum airbreathing Mach number?
- Are sub-systems being integrated or are many stand-alone type systems proliferating?
- Is there a crew?
- Are common functions being matured to modularize and integrate?

This assessment process is used to guide conceptual designer choices in the proper direction for improving operations. The ability to determine a "sense of direction" and a likelihood of achieving objectives (cost and flight rates) *IF* assumptions (design, technology, payload) are in fact achieved, was precisely one of the goals in having created the AATe© tool.



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Space Solar Power

Exploratory Research and Technology, Earth to Orbit Systems

Example Inputs to Outputs

Argus SSP Vehicle

Vehicle Characteristics:

Gross Weight:	590,500 kg.
Dry Weight:	75,000 kg.
Payload Weight:	20,000 kg.
Mass Ratio:	5.592
LOX/LH2:	3.765
SLS T/W:	0.7

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Plus other vehicle characteristics information as provided by concept developer…Fluid selection, margin, transition Mach #, ...

IN

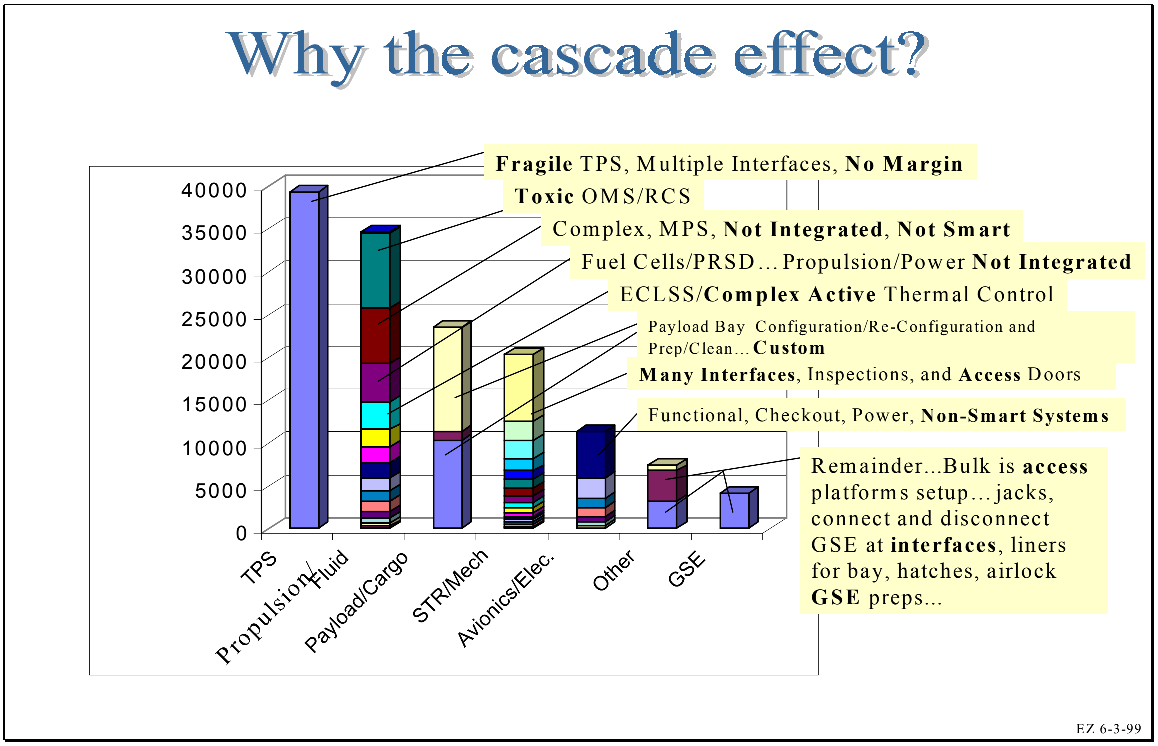
IN

Payload/Cargo Demand Per Year (Mlbs)

0.4	34
Shuttle Like	**One Tower**
OUT	**OUT**
Flight Rate Capability per Vehicle per Year (Here Under-Utilized) = 33 e.g. Requires 1 Vehicle	**Flight Rate Capability per Vehicle per Year (Here Properly Utilized) = 33 e.g. Requires 24 Vehicles**
Apx. 3 days of launch functional activity and 7 days of turnaround functional activity.	**Similar activity but amortizes fixed costs faster**
$~500/kg	**$~226/Kg**

Plus more detailed breakouts by Spaceport activity

FIGURE 8.0 Inputs & Outputs for an operational assessment of proposed Earth-to-Orbit space transportation.



Why the cascade effect?

Fragile TPS, Multiple Interfaces, **No Margin**

Toxic OMS/RCS

Complex, MPS, **Not Integrated**, **Not Smart**

Fuel Cells/PRSD… Propulsion/Power **Not Integrated**

ECLSS/**Complex Active** Thermal Control

Payload Bay Configuration/Re-Configuration and Prep/Clean… **Custom**

Many Interfaces, Inspections, and **Access** Doors

Functional, Checkout, Power, **Non-Smart Systems**

Remainder…Bulk is **access** platforms setup…jacks, connect and disconnect GSE at **interfaces**, liners for bay, hatches, airlock **GSE** preps…

FIGURE 9.0 Shuttle resources; labor on the world’s first and only operational reusable space transportation system. These are DIRECT Man-hours per orbiter flow, OPF (orbiter processing facility) Orbiter activity only. Does not include SSME (Space Shuttle Main Engine) or OMS/RCS (orbital maneuvering system/ reaction control system) Offline Work, ET, SRB, MLP, or Pad. STS-85 Snap-shot (late 1997). Total~140,000 Mhrs.

Note that conceptual vehicle designers are not typically accustomed to thinking about the operations impacts of their design choices. Instead, maximum performance, minimum gross weight, or minimum dry weight are often primary design objectives. A change toward the use of COTS subsystems for example adds weight and size to the design. It is only through the use of a tool like AATe© that the net positive effect on fleet size (and thus cost) is determined.

The assessment of any future system requires an understanding of current systems that will have a historical linkage. Shuttle, AATe©’s anchor system, was originally proposed as a system with a 10 to 15 flight per year capability per vehicle. Costs were to be 10’s and not 100’s of millions per flight. Actual results were about 2 to 3 flights per year per vehicle. Although marginal costs are actually quite competitive today (if anyone was allowed to pay just the $80 to $90M marginal) large fixed infrastructure contributes to overall average costs per flight of over $300M per flight. A review of Shuttle resource intensiveness by sub-system is shown in Figure 9.0.

The challenge in ETO for SSP is how to define systems taking not over 100 days per vehicle to turnaround, but instead about 1 week, or less. (A quick calculation could show that the direct labor that might be available for the SSP ETO would be on the order of only a thousand labor hours)

SSP ETO OPERATIONS RESULTS

The iterative process of improving the initial HRST vehicle designs was conducted for all three candidate vehicles. NASA used AATe© to identify key design sensitivities for each vehicle concept, then recommended the changes to Georgia Tech vehicle designers. When the change implied a weight addition, the vehicle designers resized the new, heavier vehicle to meet the payload delivery requirements and sent the results to NASA to confirm that the operational benefits were still in place. In most cases the weight increases were small (10% - 15%) compared to the operability gains measured in increased flight rates per vehicle (faster turnaround time). The operational assessments of the concepts previously outlined, as updated for AATe© version 1.0, are given in Table 3.0. The data is in expected flights per airframe per

TABLE 3.0 SSP Operability Improvements.

Concept	**Initial (HRST) Flight Rates**	**Improved (SSP) Flight Rates**	**% Gain**
Argus	~ 21/year	~ 46/year	220%
Hyperion	~12/year	~ 35/year	290%
ACRE-92	~ 13/year	~ 34/year	260%

year. Higher numbers are best and result in lower fleet size requirements to meet a given mission model.

These assessments were total system assessments capturing vehicle and ground activity. The entire "spaceport" as a function of people, facilities, equipment and vehicles are included. These spaceport "modules" modeled in AATe © comprised 12 areas of costs with 4 also being actual cycle time delimiters. These were:

- PAYLOAD / CARGO PROCESSING
- TRAFFIC / FLIGHT CONTROL FACILITIES
- LAUNCH (Cycle Time Contributor)
- LANDING / RECOVERY (Cycle Time Contributor)
- TURN AROUND (Cycle Time Contributor)
- INTEGRATION (Cycle Time Contributor)
- DEPOT / MAINTENANCE
- SUPPORT / INFRASTRUCTURE
- CONCEPT UNIQUE LOGISTICS
- OPERATIONS AND MANAGEMENT
- EXPENDABLES
- COMMUNITY INFRASTRUCTURE

It is important to note the outcome of such assessment is not "exact". There is a significant amount of uncertainly in the modeling process. Can we really determine whether it's exactly 34 or is it 35 flights per airframe per year for ACRE-92? Rather, the goal is to use available the data, the knowledge base, and the expert assessment of the impacts of the design changes to the vehicle to support the sense of direction that the new vehicle would represent some degree of improvement over the initial 13 flights per year result

ECONOMIC RESULTS

The new operations data in Table 3.0 was used in an overall economic model of the SSP ETO deployment problem[3]. Note that subsequent design studies determined that larger payloads (40 MT vs. 20 MT) would be advantageous for the RLV developer and operator. Larger payloads reduce annual flight rate and therefore reduce fleet size. At the same time, the larger payload results in a larger, more expensive flight vehicle, but the overall trade favors the larger payload. Representative results for the 40 MT *Argus* SSP concept are given in Table 4.0 for the baseline 30 year SSP mission[3]. Note that the internal rate of return is shown to an attractive 22% for this venture even with a very low price of only $400/kg for cargo delivered. Prices are in 1999 US dollars.

TABLE 4.0 SSP Economic Results for *Argus*.

Argus	**Result**
Fleet Size	14
Peak Flight Rate	491 flights/year
Payload Launch Price	$400/kg
Total Flights in Model	13,514
Total SSP Mass Delivered (30 yr.)	513,513 MT
Total SSP Revenue	$205.4 B
Best Ops Cost	$2.43 M/flight
Fleet Procurement Cost	$14.0 B
Net Life Cycle Cost to RLV developer/operator	$75.1 B
Internal Rate of Return	22.03%

These results are highly dependent on the assumptions and contributing costs factors used. A key conclusion of the SSP study was that up front costs (non-recurring costs) have a significant impact on the economic return on investment for the RLV developer. *Argus* is a launch assist concept. For the present study, it was assumed that a government entity (federal or state) would provide the ground infrastructure for the spaceport (including the Mag-Lev track system). To further reduce up-front costs, the government was also assumed to be a cost sharing participant in the vehicle and engine development programs (bearing 20% of the airframe development and 100% of the engine development). In addition, it was assumed that the RLV developer would be eligible for a low interest rate, government backed loan of only 7.5% to support vehicle development and fleet acquisition. These assumptions have a significant effect on the economic success of this program. In all cases, the RLV developer and operator was required to pay 100% of hardware acquisition, operations, and financing costs.

NEXT STEPS

To improve the current operability results, better models and further refinement of existing models are required. Improvement is particularly needed in the area of how design features affect *development* as well as operations costs. For example, while features such as reliability may be flowed down to some degree to affect operations, the (positive or negative) effects of the same types of issues on development costs are not adequately modeled. The addition of overall reliability to a concept may eliminate test, checkout, and R&R of components. Yet how much will it cost up-front to mature such systems and components? Major areas for cost/cycle time modeling improvement include:

- Component and overall system reliability (system/sub-system maturity, failure rates)
- Component design life (# of flights)
- Integration issues – joining of system/subsystem functions into common hardware.

Better conceptual models for these areas are required to assist technology / infrastructure investments.

CONCLUSIONS

The overarching question to be answered by this task of the SSP study was to determine:

> "Is it feasible to create ETO transportation systems, within the next generation, that can meet mass delivery and price requirements of SSP, while still returning an acceptable economic return to the launch vehicle developer/operator?"

It appears that given proper emphasis on vehicle operability, the answer to the question is "yes". The established SSP price goal of only $400/kg of payload represents a significant reduction in revenue per flight compared to current systems. However, highly reusable vehicles will benefit from the tremendous amount of traffic to support SSP deployment. At high, sustained annual flight rates, economies of scale and operational efficiencies allow for a reasonable return on investment of more than 22% for the RLV developer and operator.

In addition to low operations cost and high fleet utilization rates, a key factor in the economic success of this venture is participation by the government to reduce up-front costs. Using the argument of a common "spaceport", a case for investment can be made for such space transportation systems development. Public and private sector investments would be required, but long-term public payoff is likely to be high. In light of the potential gains, not just for enabling such enterprises as space solar power satellites, but for enabling a host of secondary economic activity, further refinement of such models, assessments and concepts/technologies is desirable in the near term.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the work and support in this project of Carey McCleskey and Russel Rhodes of NASA Kennedy Space Center, and of intern Rebecca Cutri-Kohart of the Georgia Institute of Technology.

REFERENCES

1. Mankins, John C. (1997) "A Fresh Look at Space Solar Power: New Architectures, Concepts and Technologies," International Astronautical Federation (IAF).
2. Orlebar, Christopher (1994) "The Concorde Story, 21 Years in Service," British Airways and Osprey Publishing. Values for table, such as flights per year per vehicle for S/N 206, Registration G-BOAA
3. Olds, John R. (1998) "Launch Vehicle Assessment for Space Solar Power," Final Report for NASA MSFC Grant NAG8-1547, Georgia Institute of Technology, Atlanta, GA, December 16, 1998.
4. Prices for Concorde flights quoted, August 1999, by British Airways.
5. NASA (1998) "An Operational Assessment of Concepts and Technologies for Highly Reusable Space Transportation," NASA HRST Integration Task Force, including JSC, KSC, LaRC, MSFC and SSC.
6. Zapata, Edgar (1999) "Space Transportation Operations Cost Modeling and the Architectural Assessment Tool – Enhanced," International Astronautical Federation (IAF) Paper IAA-99-IAA.1.1.01