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ECONOMIC ANALYSIS
ON THE SPACE TRANSPORTATION ARCHITECTURE STUDY (STAS) NASA TEAM

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Abstract

The National Aeronautics and Space Administration (NASA) performed the Space Transportation Architecture Study (STAS) to provide information to support end-of-the-decade decisions on possible near-term US Government (USG) investments in space transportation. To gain a clearer understanding of the costs and benefits of the broadest range of possible space transportation options, six teams, five from aerospace industry companies and one internal to NASA, were tasked to answer three primary questions:

- if the Space Shuttle system should be replaced;
- if so, when the replacement should take place and how the transition should be implemented; and
- if not, what is the upgrade strategy to continue safe and affordable flight of the Space Shuttle beyond 2010.

The overall goal of the Study was "to develop investment options to be considered by the Administration for the President's FY2001 budget to meet NASA's future human space flight requirements with significant reductions in costs." This emphasis on government investment, coupled with the participation by commercial firms, required an unprecedented level of economic analysis of costs and benefits from both industry and government viewpoints.

This paper will discuss the economic and market models developed by the in-house NASA Team to analyze space transportation architectures, the results of those analyses, and how those results were reflected in the conclusions and recommendations of the STAS NASA Team.

Background

One of the traditional roles of governments is to provide or nurture infrastructure upon which commerce is built. Highways, ships, airports and railways are historical examples of transportation infrastructure that governments around the world have either built or enabled. In the past, when a particular transportation industry has been too immature to satisfy the requirements of the United States Government (USG), the Government has faced a choice of either doing the transportation job itself or helping the industry to mature enough to do it.

The USG now faces that decision again, this time in its requirements for human space transportation. The launch vehicle industry closely parallels historical transportation industry examples, and this enabling transportation infrastructure could have significant benefits in both strategic and economic terms. The USG could make long-term investments to enable the exploitation of the resources of space; however, such an investment would need to be justified by a clear strategic or economic benefit to the US.

The President's National Space Transportation Policy[1] describes a "decision...by the end of the decade" about the development of a next-generation reusable launch vehicle (RLV) that could serve national space transportation needs; however, this is not just one decision, made by NASA, which is scheduled for December 31, 1999. Rather, this must be a complex series of interdependent decisions and contingent commitments made by several USG entities, multiple space transportation companies, and their customers and suppliers. The proper timing for the execution of this sequence will be determined by the optimum alignment of the financial and strategic interests of the USG and aerospace industry, but investments and policy decisions by the USG could greatly accelerate or decelerate the pace.

Earlier this year, NASA undertook a comprehensive look into the future of space launch in the United States, the Space Transportation Architecture Study (STAS). As the name implies, the study was to evaluate NASA's options, not only at the level of individual launch vehicle elements or systems, but also at a much higher "architecture" level, which includes the technology and infrastructure investments associated with multiple launch systems and their possible benefits to NASA. *This paper does not reflect the final economic analysis of the Space Transportation Architecture Study, nor the overall conclusions of the STAS, only those of the internal NASA Team.*

The primary questions concerned NASA's human space flight requirements. With its limited budget, should NASA pursue significant upgrades of the venerable Space Shuttle, adaptation of other existing systems such as expendable launch vehicles (ELVs) to NASA human spaceflight requirements, or investment in new RLV systems? Can NASA's human space transportation requirements be commercialized, or should the agency operate the Shuttle until the nation provides funding for NASA to develop the next generation launcher?

NASA Goals

Reducing the risk and cost of access to space is third on NASA's list of its most important priorities. Even the high reliability of the Shuttle, relative to ELVs, leaves too much chance for loss of human life, and the cost of access to space is the major obstacle to commercial development of space and continued human exploration of the Solar System. Since NASA's top two priorities, the safe continued flight of the Space Shuttle and the successful construction of the International Space Station, are oriented toward implementing existing programs, NASA's third priority, safer, lower-cost access to space, is its number one development goal.[2]

Some progress has already been made over the last few years in the reduction of launch costs and prices. The EELV Program is reducing commercial expendable launcher prices by as much as 35% below the previous generation. Space Shuttle Program costs have declined by a similar percentage over the last decade. However, to orbit the amount of material necessary to continue human exploration again, these improvements must be improved upon by an order of magnitude.

A less visionary—but more immediate—need of NASA is to reduce the predicted cost of serving the International Space Station (ISS) with logistical support and crew rotation. Moreover, even the relatively-high reliability levels of the two current ISS-capable crewed launch systems, the Space Shuttle and the Russian Soyuz, leave a significant possibility that an event will occur that will interrupt the flow of logistics to the ISS. The need for increased alternate access to the Station in its operational phase makes development of a new human-capable system desirable.

At the same time, the Space Shuttle provides many valuable capabilities to NASA, some of which may not be duplicated by a vehicle that is designed to be successful in the commercial launch market. Space transportation is central to NASA's activities, so any move toward "outsourcing" this function must be deliberate and well-conceived, considering not only the cost of transportation but also the unique characteristics of both incumbent and new architectures.

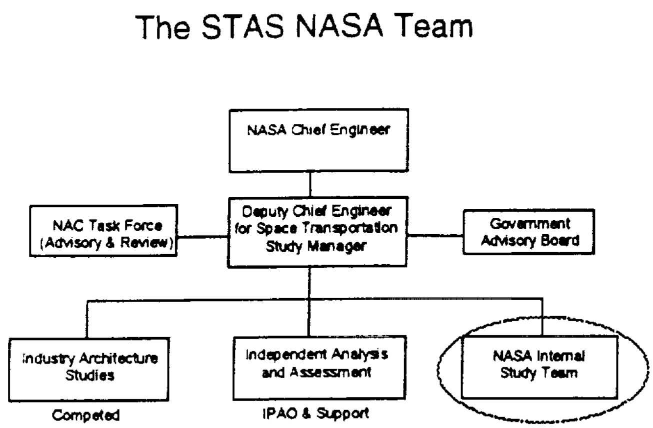

Figure 1: Space Transportation Architecture Study Team Structure

The STAS NASA Team was only one part of a much larger effort, managed by NASA's Deputy Chief Engineer for Space Transportation under the direction of the Chief Engineer (Figure 1). Six working-level teams, five from aerospace industry companies and one internal to NASA, participated in the evaluation of architectures. After these six teams completed their work, an independent evaluation and normalization of their results was conducted by the NASA Independent Program Assessment Office (IPAO) at Langley Research Center. Advisory groups received mid-term and final briefings from each working-level team and the independent evaluation group. Work is proceeding on integration of the results into a NASA space transportation investment strategy.

The in-house NASA Team brought several unique approaches to the STAS. Because it was not advocating any proprietary solutions, this team could objectively evaluate the broadest range of possibilities. While industry teams concentrated on the STAS baseline analysis period out to 2020, the NASA Team analyzed both the baseline period to 2020 and an extended period to 2030 that more completely described the benefits of new systems, especially from the government perspective. The NASA Team also evaluated their Architectures on their support for human exploration of Mars. Most importantly, the in-house team developed a flexible framework for analysis, economic modeling, and decision support that can be easily expanded and updated in the future as more information becomes available about NASA's space transportation architecture options.

The ten NASA Team members represented six NASA field centers and the Air Force Research Laboratory. In the three-month span to which the NASA Team effort was limited, several accommodations were necessary to produce a meaningful product. While the STAS guidelines described a broad range of scenarios and evaluation criteria, the NASA Team kept their analysis at a high level and focused it on the most probable representative scenarios and a few discriminating, quantifiable metrics. Their primary scope was commercialization of NASA's earth-to-orbit human transportation requirements, in the context of the growing commercial uncrewed launch market.

Subteams were formed to focus on Architecture Options, Vehicle Elements, Economics, Safety and Reliability, and Capabilities. Five representative Architectures framed the analysis:

1. Shuttle with limited upgrades;
2. Shuttle with a Reusable First Stage (RFS) to replace the Solid Rocket Boosters;
3. Evolved Expendable Launch Vehicles (EELVs) with a new Crew Transfer Vehicle (CTV);
4. a two-stage to orbit (TSTO) RLV with CTV; and
5. a single-stage to orbit (SSTO) RLV with CTV.

Options were identified for analysis within each Architecture, such as evolution of the RFS into a smaller, uncrewed commercial satellite launch system. The new launch vehicle elements within the Architectures, such as the RFS, TSTO and SSTO, were based on previously-studied concepts that had been defined in sufficient technical detail to facilitate high-level analysis.

The top-level criteria chosen by the NASA Team fell into two categories: quantitative and qualitative. The qualitative criteria—Resiliency, Continuity, Competition, Mission Capabilities, US Competitiveness, and US Technological Leadership—were evaluated in Team discussions, since metrics and tools for evaluating Architectures against these criteria could not have been developed in the time available to the NASA Team.

The four quantitative criteria were:

- Reliability (Probability of Mission Success);
- Safety (Probability of Crew Safe Return);
- Technical Risk (Probability of Successful System Deployment); and
- Discounted Life Cycle Cost to NASA.

Economic Analysis Approach

The primary economic metric for each Architecture was the total discounted life-cycle cost (LCC) to satisfy NASA's space transportation needs from earth to orbit. This LCC comprises three elements: International Space Station (ISS) logistics and crew rotation mission costs, NASA science launch costs, and space transportation technology costs.

For existing space transportation systems, those budgets (in the 2004 time frame) were estimated to be $2.4B for ISS missions on the Shuttle[3], $350M for science flights on ELVs , and $300M in space transportation technology funding, for a total of $3.05B per year (in 1999 dollars). This available budget stream was defined as the Reference Budget, which summed to $35.3B (to 2030, 7% real discount rate). The Reference Cost for satisfying NASA's existing space transportation requirements, not including technology funding for future space transportation, totals to $2.75B per year, or $32.0B discounted to 2030.

For each Architecture, two scenarios were examined: commercial and USG-funded. That is, the investment in significant upgrades or a new launch system could be made primarily by either industry or NASA. This investment, or non-recurring cost, includes the development and production costs of upgraded elements or new vehicles as well as the necessary facilities. Whether upgrades or new launch system investments are made by the USG or industry, some non-commercial elements, such as a CTV designed specifically for ISS crew rotation, were assumed to be funded by the USG.

In a government-developed scenario, NASA's LCC would simply be the total of technology programs, non-recurring costs and operating (recurring) costs for all required elements. While NASA would bear the entire investment in non-recurring costs, benefits from this approach would be reaped downstream because NASA would pay only recurring costs—not price, which also includes industry profit—for each flight. However, national space policy precludes USG launchers from competing with commercial launchers, so a USG-funded system would not be able to service the commercial launch market.

In a commercial scenario, a company would make the necessary investments to field a new launcher, and then NASA would purchase services from the commercial operator, rather than operating the system. If new system investments are made by industry, they do not appear in the NASA LCC directly, but indirectly through two categories of NASA costs: the prices per flight charged to NASA, and the costs of incentives given to the launch provider to encourage the development of a human-capable system.

The NASA LCC for each commercial Architecture, then, includes:

- ISS mission costs, including flight prices and NASA-funded, ISS-specific crew and cargo transfer systems;
- NASA science mission flight costs;
- the cost of the technology program necessary to realize a new system; and
- the costs to NASA of incentives offered to industry.

Economic Modeling

The emphasis on commercial involvement in the STAS demanded a great depth and breadth in analysis. Not only must cost and benefits be tallied on the government's side, but also on that of industry, to ensure an acceptable level of profitability. In addition, the business case is based partially on the ability of the new launcher to satisfy the requirements of the commercial launch market, which USG-owned vehicles cannot service according to US space policy. Thus, the suitability of each launch system for the commercial market must be modeled to properly address the extent to which an Architecture can leverage commercial markets to lower NASA's LCC.

To facilitate a quick start and rapid turnaround of analysis, three existing models were used (and significantly enhanced) for the STAS NASA Team effort by the Economics Subteam, led by Joe Hamaker (Manager, Engineering Cost Office, NASA Marshall Space Flight Center). These models were developed to model specific aspects of launch vehicle economics: commercial viability, market suitability, and NASA life-cycle cost.

The first model, the RLV Economic Case Study Model, was developed to evaluate business cases constructed around a newly-developed RLV. In a broader sense, it is equally applicable to an existing system such as the Shuttle, if it is commercialized; that is, it requires an initial investment from the commercial operator and provides returns on the investment. This model has been used previously to explore the effects of a wide range of launch industry incentives, including government capitalization, government guaranteed loans, various tax incentives and other forms of financial aid, on both the commercial launch system business case and on the net present value of government benefits from such a next-generation launch system.[4]

The second model, the RLV Market Analysis Model developed by Frank A. Prince, estimates the annual flight rate of a commercial launcher, given a price per flight and vehicle capability. The STAS guidelines listed several sources for mission and market data[5], which were incorporated into the model for the NASA Team analysis. Three different methods are used in this model to convert mission data to flight rates in three types of market segments: inelastic (ISS), non-elastic (existing), and elastic (emerging).

Inelastic market segments (such as the US ISS logistics manifest) do not grow, nor do their purchasing habits change, as a launch provider's price changes, as long as the price is below a certain threshold. Non-elastic market segments, such as existing satellite communications service providers, also do not grow as price is reduced; however, a lower-priced provider may capture more of the market from its competitors. This market capture for a new launch system is estimated in the model by comparing its price per flight to the database of competitors with a similar weight capacity to a particular destination orbit.

Elastic market segments, on the other hand, grow as prices are reduced, which indicates the creation of a new customer base. If a new space transportation system were to reduce prices enough to elicit an elastic market response, not only would it corner that market segment, but it would also create new space businesses, providing macroeconomic benefits to the US in increased employment and to the USG in increased personal and corporate income taxes.[6]

The third model, the STAS Life-Cycle Cost Model, was adapted for several uses in this analysis from the Access to Space Life-Cycle Cost Model by David Taylor. One version of this model was used to integrate the other models, summarizing the NASA discounted life-cycle cost, both to the baseline period of 2020 and to the extended 2030 horizon. Another version of the model was used to provide detailed yearly industry costs for the RLV Economic Case Study Model. Yet another version was used in the USG-funded cases, where no industry analysis was necessary.

Assumptions

System-level cost estimates were constructed for development, production, operations and facilities for elements within each Architecture and its options. These life-cycle cost estimates assumed maturation of technology and development culture, projecting 40-60% reductions in vehicle development and production cost from historical experience, e.g. the Space Shuttle, and more significant operations cost and turnaround reductions, even for commercial Shuttle Architectures. Assumption of reductions in operations cost of approximately 25% below the $2.4B projection were necessary to close the business cases for the commercialized Shuttles in Architectures 1 and 2.

Assumed improvements in both technology and management must occur for these costs to be achievable. The technologies used in development of the launch systems must all have reached a maturity on NASA's Technology Readiness Level (TRL) scale of six or greater, which means that they have been used in an operational launch vehicle, tested in a system-level flight demonstration program (such as NASA's Future-X), or ground-tested with relevant environmental stresses to simulate the operational environment, including cycle testing. In contrast, the immaturity of some then-cutting-edge technologies used in the Space Shuttle increased its development cost and schedule and still increase operations costs and turnaround time. In a commercial environment, immature technologies are recognized as a threat, and they have a more difficult time buying their way into the launch system design.

Perhaps more importantly, the management environment must be structured to eliminate the major causes of project schedule slip and cost overrun and to ensure that the system meets its customers' needs. Requirements must be well-structured, well-allocated, logically traded, and very rarely modified. Procedures must be streamlined and specifications tailored to reduce non-value-added effort. Multi-discipline product teams at every level must have the proper tools, including not only hardware and software, but also authority, responsibility, and direct lines of communication.

Although cost estimates assumed "new ways of doing business," the aggressiveness of these estimates was tempered by a thorough accounting of other costs. First, the costs of technical risk were included, specific to each Architecture. A probability distribution of likely schedule slip was calculated based on the characteristics of the vehicle system, then translated into an expected value of cost. Next, an estimate of the cost of the technology program necessary for reaching TRL 6 was included. Finally, the cost of catastrophic unreliability for each Architecture was included, based on several cost impacts: the production of additional vehicles to replace expected flight capacity loss due to catastrophic events; investigation of the cause of failure; cost of the remedial actions to the remaining fleet; and loss of revenue during the system down time for investigation and fleet remedies. (The expected cost of replacing a Shuttle Orbiter was not included in Architectures 1 and 2, since the loss of one Orbiter would not jeopardize the ability of the system to service the predicted mission model.) In estimation of all cost components, relative consistency of analysis and valid differentiation across the different Architectures were valued more than the absolute values of the cost estimates, which cannot in any case be accurately described by a deterministic, point value estimate.

Closed business cases were constructed for each commercially-developed launch system project, with an assumed average before-tax hurdle rate for equity investors of 25% per year. Business cases were closed, i.e., adjusted to 25% before-tax return on equity (BTROE) by increasing NASA ISS mission price per flight (PPF). In this way, ISS PPF was used to transfer benefits between Industry and the USG. (Note: a 5% change in industry BTROE, near 25%, results in an opposite change of roughly $1-1.5B LCC to NASA, discounted @ 7%.)

Of course, industry will not voluntarily limit itself to any particular level of profitability. In order to obtain lower launch prices, given that the costs of the launcher would still permit profitable operation, one or more of several mechanisms would be required. These mechanisms could include advance purchase agreements for launch services, government regulation, partial government ownership, or market-based competition. In any case, this analysis assumes that industry profitability in excess of 25% BTROE is returned to NASA through reduced ISS mission PPF.

Another way to transfer benefits, from the USG to industry, is through government incentives. The Economics Subteam's analysis indicated that it would be in NASA's best interests to incentivize a commercial launch provider to either develop a new ISS-capable system or commercialize existing systems. The baseline incentives package, $1B in development assistance and a government-guaranteed loan, was chosen based on previous work on the cost-effectiveness of various government incentives for commercial launch systems, which was verified in the Economics Subteam's early analysis of the Architectures adopted by the STAS NASA Team.

STAS NASA Team Conclusions

Unfortunately, no significant LCC discrimination was found between most Architectures, although each was different in terms of investment profile and potential savings, as shown in Figure 2 below. The

Architecture	NASA Investment	Viability For Commercial Development	Potential to Lower NASA Annual Cost	Potential to Address Commercial Launch Market
Architecture 1 Shuttle with limited upgrades	Low	Some	Medium	Low (0 to 5 flights per year)
Architecture 2 Shuttle with RFS upgrade	Medium	Some	Medium +	Low (0 to 5 flights per year)
Architecture 3 EELV with crew/cargo transfer vehicles	Relatively high	Little (except EELV)	Low (due to expendable EELV)	Existing NASA, DOD & comsat market (but not elastic market)
Architecture 4 TSTO	High cost (but gov't only pays incentives)	High (with gov't incentives)	Potentially high	Existing and elastic market
Architecture 5 SSTO	High cost (but gov't only pays incentives)	High (with gov't incentives)	Potentially high	Existing and elastic market

Figure 2: STAS NASA In-House Team Economic Summary of Commercial Architectures

discounted LCC to NASA of each Architecture commercial scenario to 2030 was below the discounted total Reference Cost of $32.0B, and all were within 10% of each other. The USG-funded scenario for each Architecture had a higher LCC to NASA than the commercial scenario, due to removal of the benefits of leverage with commercial launch markets.

The commercial scenario analysis excluded Architecture 3, EELV, because a commercial analysis could not be done. The NASA Team did not have access to technical, cost and revenue data for the two competing EELV product lines, so the investment and return criteria used for the other commercial scenarios could not be run. If the EELV price per flight could be lowered about 40% from current quoted prices, the EELV Architecture LCC to NASA would be competitive. Using publicly-available prices for EELV flights, though, the LCC to NASA was estimated to be significantly higher than the other Architectures and the Reference Cost, and even slightly higher than the Reference Budget.

Each Architecture was found to have strengths and weaknesses among the other criteria, but no one Architecture rated highly among all criteria. Vehicle systems with CTV capability for crew survival and recovery were evaluated highly on safety criteria; the Shuttle-based Architectures had a relatively low investment and technical risk. The NASA Team agreed to summarize their findings in the following way.

> Not enough knowledge is available today to commit to a Shuttle replacement.
>
> If NASA is primarily interested in maintaining the unique capabilities of the Space Shuttle (servicing, crew, etc.) while reducing its costs for ISS transportation at low risk, it should pursue Architecture 1, knowing that eventually Shuttle will have to be replaced. However, Shuttle's flight rate capability (10/yr) limits commercial potential and will not expand the U.S. share of space market.
>
> If NASA is primarily interested in stimulating the commercial market and enabling an expansion of the U.S. market share, it should pursue Architecture 4 or 5.

Additional Observations

The achievement of true competition in a very limited and complex human transportation market will be very difficult in the near-term commercial launch marketplace. The level of USG and industry investment necessary to develop one new human-capable launch system would not double if two competing systems were developed, but the additional investments would be significant. Not only would non-recurring costs increase significantly, but each system's leverage with commercial markets would be reduced, due to the addition of an additional competitor into what is still a fairly immature market. Subsequent analysis has estimated that, on the USG side, the additional investment to obtain alternate human access to space, discounted over the life cycle to 2030, could near $10B, about a third of the total Architecture discounted LCC.

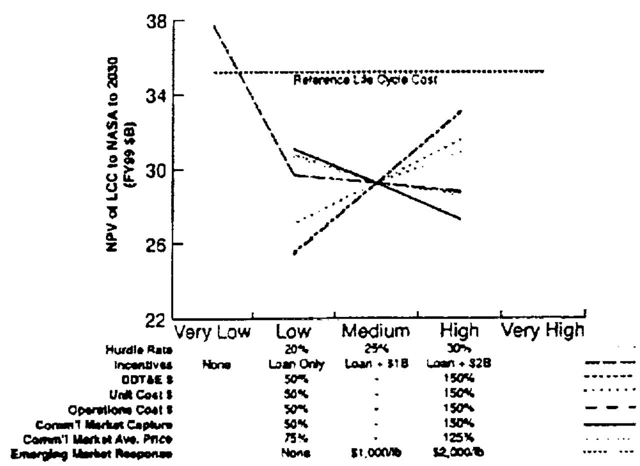

Figure 3: Single-Stage to Orbit (Architecture 5)

NASA Life-Cycle Cost Sensitivities

Several sensitivity analyses, as shown in Figure 3, were conducted to identify primary economic drivers in the Architectures. Since the time-value of money is such a powerful factor in a commercial environment, the NASA LCC of the SSTO Architecture is as sensitive to the earlier 6 years of development cost as it is to the later life-cycle operations cost over the 21 years of flights. (In the above graph, these two lines lie atop one another, slanting up and to the right.)

Even if a second-generation RLV could be financed solely by industry, the price levels required by industry to provide adequate returns for investors—while amortizing loans at high-risk lending rates—would probably be too high to reduce NASA's price per flight or to open significant new launch service customer markets. However, government investment in RLV development, in the form of incentives, could increase profitability and reduce risk for launch service providers, ultimately reducing NASA's cost much more than the cost of the incentives. In the commercial scenarios of every Architecture, incentivized cases showed a lower discounted LCC to NASA than non-incentivized.

In particular, the government-guaranteed loan was shown to be not only the most effective incentive considered, but the single most significant factor in the viability of the business case for a commercial launch system—and thus the most efficient USG action to enable reduction of launch prices. As shown in the Architecture 5 sensitivity analysis graph (Figure 3), the only excursion that increased LCC above the Reference Budget was the removal of the government-guaranteed loan (bold dashed line toward the left axis). Sensitivity analyses of other commercial Architectures yielded similar results.

Subsequent analysis indicates that tax incentives, for the same effectiveness, have much greater costs to the USG. For example, the guaranteed loan has similar effects on launcher after-tax equity returns to those of an 80% research and experimentation credit (with no exclusions or limitations), and greater effects than a tax holiday that lasts for the entire life of the project.

Long-term investment in transportation technology and infrastructure generates broad societal benefits and is an appropriate and common historical role for governments. Historically, these investments are initially justified through projected benefits to national security or world leadership. In the absence of compelling military investments for development of the next frontier, though, the role of transportation infrastructure development for commerce and settlement falls to civil agencies, such as NASA and the US Departments of Commerce and Transportation.

In order to justify these investments, however, the uncertainty surrounding these analyses must be reduced or quantified. Simple, user-friendly tools for discounted cash flow analysis and US Government investment planning must be developed, to encourage wider use of these most important and gravely under-utilized techniques during technology planning and design trade studies. The emerging space market must be more rigorously studied to provide a much-needed update to the 1994 Commercial Space Transportation Study (CSTS). Macroeconomic models could then be refined to portray more completely the broad range of benefits from lower-priced launcher development outside of NASA LCC, such as military launch savings and employment and tax revenue increases. Of course, technology uncertainty must be strategically reduced through continued flight and ground test programs. Finally, analysis and simulation tools must be improved to properly evaluate alternative concepts and investments, including explicit, realistic assessments of the remaining uncertainty and risk.

These kinds of smaller investments over the next few years will ensure that the larger investments to come in space transportation in the United States will bring the maximum return to NASA, the US Government, the nation, and the world.

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[1] NASA Headquarters Office of the Chief Engineer, "Space Transportation Architecture Study," http://www.hq.nasa.gov/office/codea/codeae/sta_study.html.

[2] Goldin, Daniel, NASA Administrator, in a speech to the National Space Symposium, 8-Apr-99, Colorado Springs, Colorado.

[3] NASA Headquarters Office of the Chief Engineer, "NASA's Assumed Baseline Space Shuttle Launch Costs Through 2020," http://www.hq.nasa.gov/office/codea/codeae/documentc.html.

[4] Shaw, Eric J., Hamaker, Joseph W., Prince, Frank A.; Benefits of Government Incentives for Reusable Launch Vehicle Development, Paper IAA-98-IAA.1.2.01, Proceedings of the 28th Symposium on Economics and Commercialization of Space Activities at the 49th International Astronautical Congress.

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[6] The elastic market response was based on the Commercial Space Transportation Study (CSTS), Final Report published May, 1994.