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Alternate Architecture for NASA's Space Launch Initiative

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Introduction

THE Space Launch Initiative (SLI) is a $4.8 billion effort by NASA to solicit ideas for a second-generation reusable launch vehicle to replace the space shuttle and to begin development of new propulsion systems for such a vehicle. The stated goal is to develop a launch system that is 100 times safer than the shuttle with 1/10th the cost of delivering payloads to orbit.[1] At first the SLI managers were receptive to ideas for design studies of new architecture from a wide variety of sources, but soon funding for such studies was concentrated among three teams of winners in the initial competition.[2] It is anticipated that design concepts from two of these three competing teams will be selected by the end of 2002 for further study. Then, when all factors have been carefully considered, a final decision on the design of a new vehicle to replace the shuttle will probably be made in 2006. In the unlikely event that a suitable replacement for the shuttle is not forthcoming, NASA might recommend continued use of the shuttle fleet with component upgrades.

The space shuttle is officially called the Space Transportation System (STS) for its preeminent place in the national space program. Despite its one tragic failure (which probably could have been avoided with proper launch precautions), it has the best reliability record of any space launch vehicle (SLV) in the U. S. inventory.[3] In 1993 the case was made for development of the Shuttle II[4] (an upgraded version of the shuttle), but at that time NASA was more interested in pursuing development of a reusable single-stage-to-orbit (SSTO) launch vehicle to replace the shuttle. After failure of the X-33 program to demonstrate feasibility of the SSTO concept, it became clear that this concept is no longer a viable solution to the problem of finding cheaper access to space. There now appears to be general agreement on the idea of having two reusable stages in any new SLI concept. Moreover, there is still a preponderance of thinking within NASA and among its larger contractors that favors use of liquid rocket propulsion exclusively for both stages. This bias in architecture design to exclude use of solid rocket propulsion is caused by the stipulation that both stages of the new launch vehicle be fully reusable. It might prove to be a limiting factor in development of a really safe and reliable launch system to replace the shuttle. It will almost certainly have the effect of greatly extending development time for such a system with concomitant skyrocketing of costs.

Having the right concept is essential to achieving success in development of a safe and reliable launch system that will provide low-cost access to space in the 21st century. In the Apollo program it was a change in concept early on that was critical to success in the many moon landings. Direct landing on the moon after translunar flight from the Earth was abandoned in favor of using a lunar excursion module after first going into circumlunar orbit. The space shuttle is arguably the right concept of a heavy lifter for manned missions into space or for placing large and very heavy satellites in orbit. However, it was initially misrepresented as a cost-effective launch vehicle for all sizes of payload with a reasonably fast turnaround time. The truth is that the shuttle is a costly SLV with a long turnaround time because of its huge size and use of cryogenic liquid rocket propellant. Substitution of kerosene for liquid hydrogen as fuel could significantly lower recurring launch costs but would require a downsizing of the orbiter and reductions in both the size and the weight of payload.[5] Nevertheless, the basic shuttle architecture is conceptually sound with great flexibility in its size and in the choice of liquid rocket propellant.[6] The lessons learned in nearly 20 years of shuttle operation could be used to good advantage in design of an expanded and improved STS.

The purpose of this Note is to present an alternative architecture to that being studied by NASA in its SLI program to find a replacement for the space shuttle and expendable SLVs presently in use. In addition to providing a different perspective from the prevalent thinking within NASA and its contractors, the hope is that the SLI managers will want to include the architecture suggested in their overall consideration. If it should turn out that a practical and viable new launch system (with irrefutable economic advantages) does not emerge from the SLI studies, then acceptance of the proposed shuttle-derived alternative architecture could occur. Implementation of such an architecture with a modular concept for expendable components could provide a cost-effective, multipurpose launch system for NASA, the U.S. Department of Defense, and the private sector at a fraction of the cost for any system presently under SLI study. Moreover, development time would be considerably less because of the use of a highly evolved spacecraft design along with existing liquid rocket engines and solid rocket boosters. Furthermore, expanding and upgrading a proven launch system with the latest advances in technology would ensure the highest degree of safety and reliability. The proposed system architecture is predicated on the idea that a truly cost-effective space transportation system should be comprised of different-sized launch vehicles for different missions and for payloads of various size and weight. Like the Shuttle II, the smaller launch vehicles would have reusable orbiters, but they would be designed to operate in a manned or unmanned mode and would burn noncryogenic fuel in single liquid rocket engines that have a proven record of performance.

Basic Launch System Concept

The basic idea behind the proposed architecture is that, in spite of extensive SLI design studies, the space shuttle might still be the most reliable and versatile launch system that has yet been conceived. That is to say, there is probably no other system on the horizon that could outperform the shuttle as a safe and reliable delivery system for transporting both humans and cargo from ground to orbit and back. The problem then is not in safety and reliability but in cost and turnaround time. If a system based on the shuttle concept could be made much less costly and with a much shorter turnaround time, it would be a considerable improvement over the shuttle. That was the thinking behind the concept of the Mini Shuttle,[5] with a $\frac{3}{4}$-size orbiter and external tank (ET), which burns kerosene instead

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of liquid hydrogen. With the same-size solid rocket boosters (SRBs) the payload would be about $\frac{3}{4}$ that of the shuttle. Using noncryogenic fuel and downsizing both the Orbiter and ET would greatly simplify launch preparation time and lower costs, with a concomitant reduction in specific payload costs. It is important to keep in mind the fact that the shuttle concept provides a dual-purpose launch system (for carrying personnel and cargo to and from orbit). If these two functions were separated, as in some SLI architectures being studied, it is unlikely that there would be overall cost benefits. However, there may be significant cost savings in having a partly reusable launch system with several different-size vehicles that are tailored to the size of payload and the number of personnel (if any) onboard.

The best rationale for staying with the basic shuttle architecture is that it probably provides the highest degree of safety in carrying humans into space. It is a fundamental tenet of rocketry that fewer is better when it comes to the number of solid rocket motors (SRMs) or liquid rocket engines (LREs). For smaller versions of the shuttle, with noncryogenic fuel such as RP-1 (kerosene), only a single LRE in a downsized orbiter would be required, which would give the lowest probability of propulsion system failure. Thus, from a statistical standpoint it is hard to see how a safer and more reliable launch system than that of the downsized shuttle can be devised (even though there would be no engine-out capability). Furthermore, continuing use of the same basic system would obviate the need for a long development time, with less uncertainty as to final system performance and reliability. For these and other reasons it is becoming increasingly clear that a strong argument can be made for NASA to seriously consider architectures for a second-generation launch system derived from that of the space shuttle. Some shuttle-like architectures, which could comprise a reconstituted STS for use by NASA, the U.S. Department of Defense, and the private or commercial sector, are described in the following section.

Proposed Launch System Architecture

As already indicated, an architecture for a second-generation launch system to eventually replace the aging shuttle fleet should consist of several different-size launch vehicles patterned after the shuttle. However, the liquid rocket fuel for all but the largest vehicle should be noncryogenic. This means that only the largest launch vehicle would burn liquid hydrogen (to maximize payload weight capability for a given liftoff weight), with a resulting simplification in fuel handling and a saving in fuel costs for launch of the smaller vehicles. Moreover, because of the availability of proven LREs of suitable thrust burning noncryogenic fuel, only a single LRE would be required for the downsized orbiters of the smaller vehicles. A proposed architecture for four partly reusable launch vehicles comprising a reconstituted STS is shown to the same scale in Fig. 1. Nominal design specifications of components and propulsion systems for these four different-size launch vehicles are listed in Table 1. It is envisioned that all of these vehicles could be operated in an autonomous mode with a two-man flight crew or unmanned by remote control.

The Shuttle II is essentially an upgraded space shuttle with the latest advances in technology for all components. It would still have a full-size reusable orbiter with three space shuttle main engines

Table 1 Nominal design specifications for different-size launch vehicles in a reconstituted STS

Specification	Shuttle II	Mini I	Mini II	Mini III
Orbiter scale	Full size	3/4 size	1/2 size	1/3 size
Orbiter liftoff weight, lbm	180,000	80,000	45,000	20,000
Payload bay, ft	15 × 60	11.25 × 45	7.5 × 30	5 × 20
Payload to low Earth orbit, lbm	52,500	38,250	21,500	5,530
Liquid rocket engine(s)	3 SSMEs	1 RD-180	1 AJ26-58	1 LR87-AJ-11
Oxidizer/fuel	LOX/LH2	LOX/RP-1	LOX/RP-1	N2O4/Aerozine-50
Average sea level thrust, lbf	1,125,000	860,200	340,000	240,000
Throttling capability	67–104%	40–100%	50–109%	100% only
External tank scale	Full size	3/4 size	3/5 size	2/5 size
Liquid propellant weight, lbm	1,556,000	1,685,600	749,650	431,370
Solid rocket boosters	2 RSRMs	2 RSRMs	2 SRMs[a]	2 SRMs[b]
Average sea level thrust, lbf	5,300,000	5,300,000	2,800,000	1,500,000
Solid propellant weight, lbm	2,220,500	2,220,500	987,000	555,150
Total liftoff weight, lbm	4,500,000	4,500,000	2,000,000	1,110,000
Liftoff thrust/weight	1.428	1.369	1.570	1.568

[a]SRMs are same as those used with Titan III SLV. [b]SRMs are 0.825 scale of those used with Titan SLV.

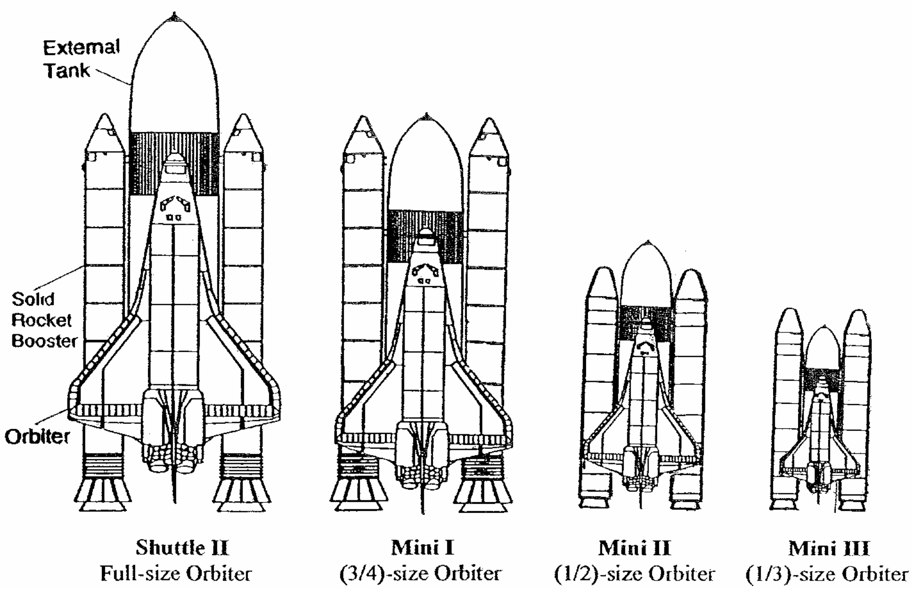

Fig. 1 Proposed launch-system architecture for a second-generation STS.

(SSMEs) burning liquid oxygen and hydrogen (LOX/LH2) but with an improved thermal protection system. The expendable ET would be made from new lightweight materials that provide adequate strength and lower cost. The reusable SRBs, now designated redesigned solid rocket motors (RSRMs), would be recovered after launch for reuse. The primary use of the Shuttle II would be that of placing the largest or heaviest payloads (up to about 52,000 lb) in low orbit and of providing a large orbital spacecraft for special extended missions with a large complement of astronauts.

The Mini I is the largest minishuttle with a $\frac{3}{4}$-size reusable orbiter and a $\frac{3}{4}$-size expendable ET. It would have a single LRE (RD-180) burning liquid oxygen and kerosene (LOX/RP-1). The reusable SRBs would be the same RSRMs used with the Shuttle II. The primary use of the Mini I would be that of placing large payloads (up to about 38,000 lb) in low orbit more cheaply than the Shuttle II and of providing a less costly spacecraft for certain manned missions with fewer astronauts. It could also be used in various ways for support of the International Space Station (ISS).

The Mini II is a smaller version of the Mini I with a $\frac{1}{2}$-size reusable orbiter and a $\frac{3}{5}$-size expendable ET. Like the Mini I it has a single LRE (AJ26-58) burning liquid oxygen and kerosene (LOX/RP-1). The expendable SRBs would be the same SRMs used as boosters for the Titan III SLV. The primary use of the Mini II would be that of placing medium payloads (up to about 21,000 lb) in low orbit more cheaply than in using the larger vehicles and of providing a relatively inexpensive spacecraft for small manned missions. It could also be used as a low-cost space ferry to transport personnel and cargo to or from the ISS.

The Mini III is an even smaller version of the Mini I with a $\frac{1}{3}$-size reusable orbiter and a $\frac{2}{5}$-size expendable ET. It also has a single LRE (LR87-AJ-11), but both oxidizer and fuel (N2O4/Aerozine-50) are noncryogenic and hypergolic. The expendable SRBs would be similar to the Titan III SRMs used with the Mini II but reduced in size by a scale factor of 0.825. With use of storable bipropellant, the vehicle could be maintained in a launch-ready condition for extended periods of time. The primary use of the Mini III would be that of ferrying personnel to or from the ISS, in space rescue situations where a quick response is necessary, and in serving as a military spacecraft for the U.S. Air Force.

The nominal payloads listed in Table 1 are for low Earth orbit. For higher orbits the size of payload would have to be reduced, or additional propellant would be required. To increase the amount of liquid propellant for the Mini I, the volume of the ET would have to be increased. An alternative procedure for the smaller Mini II and Mini III would be to also add segments to the SRBs. Thus, a modular approach to increasing the amounts of solid and liquid propellants could be developed for each vehicle to provide greater flexibility in performance.

Conclusions

Launch vehicle architecture derived from the space shuttle and modified slightly would be a sure and practical alternative to advanced architectures being studied by NASA in its Space Launch Initiative. Such alternative architecture could include a second-generation shuttle and several minishuttles of various size using noncryogenic fuel. Because all of these launch vehicles would use existing and proven propulsion systems, development time and cost would be considerably less than with any of the architectures being considered in the Space Launch Initiative. Moreover, if the cost of expendable components used with each of the minishuttles were to be a small fraction of recurring launch costs, there could be significant reductions in specific payload costs (that is, launch costs per pound of payload) from prevalent values in the launch vehicle industry. Thus, there is good reason for NASA and the U.S. Department of Defense to consider the alternative architecture in meeting their needs for reliable, cost-effective space transportation in the early 21st century.

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Simplified Algorithm for Short Target-Approach Paths in Orbit

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Nomenclature

a_{cor}	=	Coriolis acceleration, m/s^2
a_r	=	centripetal acceleration, m/s^2
r_c	=	local curvature radius of transfer arc in relative motion, m
s	=	arc length of single transfer arc, m
s_i	=	line segment of single transfer arc, m
s_t	=	total transfer distance along target approach direction, ns_i, m
t	=	elapsed transfer time, s
t_T	=	total transfer time, s
V	=	relative departure velocity (magnitude) of transfer arc, m/s
V_r	=	velocity of circular reference orbit, m/s
x, y, z	=	horizontal, radial and normal relative motion components, respectively, of transfer arc *m*
$\dot{x}, \dot{y}, \dot{z}$	=	corresponding relative velocity components, m/s
α	=	initial velocity angle relative to selected approach direction, deg
Δt_i	=	time required for single transfer arc, s
ΔV_i	=	velocity change required at end of each single transfer arc, m/s
θ	=	reference orbit central angle traversed during time t, ωt, deg
ω	=	angular rate of circular reference orbit, rad/s

Subscript

0	=	initial value

Introduction

SERVICING, support, and resupply of space systems, whether manned or unmanned, are becoming increasingly important space mission objectives.[1,2] These types of support missions will play an important role in the operation of the International Space Station (ISS) and must be performed often. The orbital dynamics of the target approach and the maneuvering activity required to achieve this objective are generally referred to as "proximity operations" and have been extensively covered in the literature, including

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