Payload Capability of Kerosene-Fueled Mini Shuttle

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Introduction

THE Space Shuttle or Space Transportation System (STS) is a beautifully designed reusable launch vehicle (RLV). With the exception of the external tank (ET), all of its components are recovered, refurbished, and used again. Despite its many critics and high operating costs, it has been a workhorse in space for nearly 15 years of service with an unparalleled record of safety and reliability. The one flight in more than 75 that ended tragically was found to have resulted from an O-ring failure in one solid rocket booster (SRB), which could have been avoided with proper launch precautions. Now, however, NASA is intent on developing a replacement spacecraft for the Shuttle that will be available in about 10–15 years and will provide considerably cheaper access to space.[1] In spite of the demise of the National Aerospace Plane (NASP) program, the concept of a reusable single-stage-to-orbit (SSTO) vehicle is still considered viable.[2,3] As a result, in 1996 a three-year contract was awarded to Lockheed Martin for development of the X-33 technology demonstrator.[4] This is a subscale prototype of the Lockheed Martin VentureStar, which is envisioned as an SSTO RLV to replace the Shuttle.[4]

In its comprehensive access-to-space study,[1] NASA considered three alternative courses of action to meet anticipated needs of the United States in launch capability through the year 2030. 1) Make necessary upgrades and continue primary reliance on the Space Shuttle and today's fleet of expendable launch vehicles (ELVs) through 2030. 2) Develop a new expendable launch system that utilizes today's state-of-the-art technology and begin the transition from the Shuttle and current ELVs in 2005. 3) Develop a new reusable advanced-technology, next-generation launch system and make the transition from today's Shuttle and ELVs from 2006 to 2010. In the final analysis, option 3 was deemed the most desirable and was recommended for consideration by the President's Office of Science and Technology Policy.

There are three alternative architectures in option 3 consisting of two reusable SSTO vehicles and one reusable two-stage vehicle. Two of the vehicles use air-breathing/rocket propulsion and one uses only rocket propulsion. Since publication of the NASA study in 1994, several option-3-type design concepts using only rocket propulsion have been reported. First, there is the NASA reference winged-body, vertical takeoff/horizontal landing (VTHL) design,[5] which is a combination of a long cylindrical fuselage and a delta wing. Second, there is a cone-shaped, vertical takeoff/vertical landing vehicle without wings.[6] Third, there is the delta-wing-shaped, lifting-body VTHL design,[7] which has evolved into the Lockheed Martin X-33/VentureStar vehicle.[4] A fourth reusable SSTO design is the wingless bent-biconic vehicle,[8] which relies on a drag chute for stabilization during transonic flight and a para-wing for landing. The authors of the paper on this last design point out some stability and control problems with the first two designs and a structural weight problem with the lifting-body design of the Lockheed Martin VentureStar.[8]

Perhaps it might be well for NASA to reconsider the viability of the SSTO RLV concept. The NASP experience was a costly and wasteful one, of both time and money, and should not be repeated. Moreover, there is a new entry into the RLV sweepstakes that just might, when combined with the Shuttle-II concept,[9] be the answer for a more-economical RLV. It is the Mini Shuttle,[10] or Mini STS, which has the potential of significantly lowering the cost of placing payloads in orbit while maintaining the safety and reliability features of the Shuttle. The main idea behind the Mini Shuttle is that of replacing the liquid hydrogen in the ET with kerosene (RP-1). RP-1 is the same fuel that was used to power the first stage of the Saturn V rocket that sent the Apollo astronauts to the moon. Although lacking the energy content of hydrogen per unit mass, RP-1 has many desirable properties that make it a very attractive fuel for use in a rocket. Moreover, it is undoubtedly the least expensive of all liquid hydrocarbon fuels.

The stated goal of NASA in the Lockheed Martin X-33/VentureStar program is to lower the cost of placing payloads in orbit from between \$5,000 and \$10,000/lb to around \$1,000/lb. However, as in the NASP program, which at its inception had the same goal, the probability of achieving this kind of reduction in cost with a dubious SSTO vehicle is not very high. Even if the Linear Aerospike rocket engine is successful, the idea of relying solely on seven of these engines functioning properly during liftoff in a reusable vehicle seems risky if not foolhardy. Then there is the critical question of whether a practical vehicle of such size and shape can be designed with so little structural weight fraction, i.e., ratio of empty weight to fully loaded weight. From the preliminary specifications, this fraction is only 0.090 for the VentureStar vehicle compared to 0.231 for the X-33 experimental demonstrator and 0.123 for the Shuttle Orbiter plus the ET. Thus, it would seem prudent for NASA to look to alternative ways of finding cheaper access to space.

The Mini-Shuttle concept represents an approach that is both conservative and time saving. In utilizing proven technology, there is the saving of long development costs with the possibility of having to start all over again with another concept (as happened when the NASP program was discontinued). Moreover, there is the advantage of maintaining a continuity of sorts in the equipment design and operation, which should provide for greater safety and less risk. Although it is difficult to estimate precisely the reduction in cost per pound of payload placed in orbit by a Mini Shuttle, the savings should be even greater than those projected for the Shuttle II.[9] The most obvious saving is that of fuel in its price per gallon and in its handling, loading, and storage. Another obvious saving is in the construction cost of the expendable Mini ET, which should be considerably less than that of the huge Shuttle ET. Then there are less tangible but substantial savings in operational costs, which would result from a redesign of the downsized Orbiter to eliminate weight, modernize various systems, and streamline launch-preparation procedures.[9] All in all, the Mini Shuttle shows promise of providing an even safer and more-economical STS than the Space Shuttle.

The purpose of this Note is to provide a preliminary analysis of payload capability for the Mini Shuttle to validate the claim of feasibility. The numerical results were obtained using an analytical method developed for vertical launch into orbit.[11] Similar computations for the payload capability of the Space Shuttle launched along the same idealized ascent trajectory confirm the accuracy of the results. The analysis also includes a comparison of the weights for various components of the Mini Shuttle and the Space Shuttle as well as a comparison of the weights and volumes of fuel and liquid oxygen required for these vehicles.

Propellant Bulk Density and Specific Impulse

In converting from cryogenic hydrogen for fuel to kerosene (RP-1), the most significant changes are in the propellant bulk density and the specific impulse of the liquid rocket propulsion system. Because the bulk density of LH2/LOX[12] is about 35% of that for RP-1/LOX, the liquid-propellant tankage required for the Mini Shuttle is only about 35% of that required for the Space Shuttle, assuming the same total weight of propellant. As it turns out, the weight of liquid propellant required for the Mini Shuttle is only about 10% more than that required for the Space Shuttle. Thus, a reduction in ET volume to about 42% of the Shuttle-ET volume is more than adequate. This would be the size of the ET if all dimensions were reduced by a scaling factor of 0.75. A three-quarter-size ET would have about half the external area and, therefore, about half the inert weight of the full-size ET. The reduction in inert weight

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is an important factor in maximizing the payload capability of the Mini Shuttle.

Rocket-Vehicle Motion During Launch into Orbit

In determining whether a kerosene-fueled Mini Shuttle would be able to attain orbital speed, with or without a substantial payload, it was convenient to utilize the stepwise analytical method already mentioned. In so doing it was assumed that the launch trajectory (and vehicle thrusting) would be similar to that in a typical Space Shuttle launch with separation of the SRBs and ET in similar fashion. After vertical liftoff and a brief period of thrusting at finite thrust angle, it was assumed that the vehicle executes a gravity turn (with zero thrust angle) to an altitude above the sensible atmosphere where, during a shallow dive and climb (with finite thrust angle), final acceleration to orbital speed takes place. This is generally what happens in a typical Space Shuttle launch with the SRBs jettisoned after burnout at 120 s after liftoff and the ET jettisoned after shutdown of the Space Shuttle main engines (SSMEs) at about 480 s.

Sizing of Mini Shuttle

From the final values of mass fraction in orbit obtained for the two vehicles, it is indicated that the Mini Shuttle could place in orbit only about 59% of the total mass of the Space Shuttle plus its payload. Thus, if the Shuttle Orbiter plus payload weighs 180,000 + 45,000 or 225,000 lb, for example, the Mini Orbiter plus payload could weigh about 132,000 lb so that a 100,000-lb Mini Orbiter could deliver a payload of about 32,000 lb.

Now the critical question in establishing the case for a Mini Shuttle has to do with the size of the Mini Orbiter or the scaling factor (SF) used with respect to the Shuttle Orbiter. If the Shuttle Orbiter could simply be shrunk in size, so that all dimensions were reduced by the SF, the mass or weight of the vehicle would be proportional to the cube of the SF. Conversely, if a Mini Orbiter $\frac{5}{9}$ the mass of the Shuttle Orbiter is desired, the SF for reduction of size should be $(\frac{5}{9})^{1/3} = 0.8221$. This is a somewhat surprising result in that a seemingly small change in Shuttle Orbiter size and conversion of its engines, together with the reduction to $\frac{3}{4}$ size of the Shuttle ET and the payload, is sufficient to permit substitution of RP-1 for liquid hydrogen. If a slightly smaller SF of 0.8 were used to size the Mini Orbiter, the fuselage could be made fatter with the plan size of the payload bay increased from 12×48 to 15×48 ft to satisfy the space station requirement.

Comparison of Mini Shuttle and Space Shuttle

An appreciation of the relative size of components of the Mini Shuttle and the Space Shuttle may be gained from the drawings to one scale in Fig. 1. The Mini Shuttle consists of a $\frac{4}{5}$-size Orbiter atop a $\frac{3}{4}$-size ET (containing RP-1 and LOX), which supports the same SRBs of the Space Shuttle. The reliability of SRBs has proven to be one of the Space Shuttle's most important characteristics in accounting for its amazing record of successful launches. In the Mini-Shuttle or Mini-STS concept, it is assumed that the size of the SRBs is unchanged with the same solid rocket propellant and method of attachment to the downsized ET. The solid propellant is a mixture of aluminum powder as fuel, aluminum perchlorate as oxidizer, iron oxide as catalyst to speed up the burning rate,

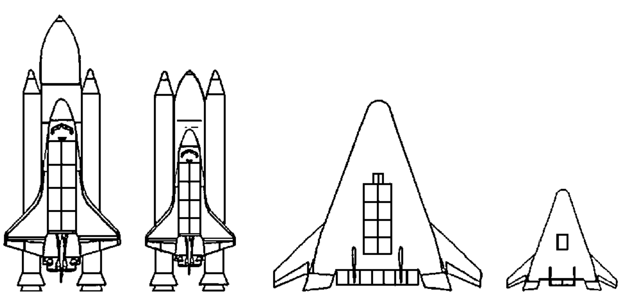

Fig. 1 Comparison of Space Shuttle size with that of Mini Shuttle and Lockheed Martin X-33/VentureStar vehicles.

Table 1 Weight comparison in pounds of Space Shuttle and Mini Shuttle

STS		Mini STS	
Orbiter and consumables	180,000	Mini Orbiter and consumables	100,000
Payload	42,916	Payload	30,905
SRBs (inert)	365,428	SRBs (inert)	365,428
Solid propellant	2,220,580	Solid propellant	2,220,580
LOX	1,332,000	LOX	1,226,832
Liquid hydrogen	224,000	RP-1	479,471
ET (inert)	73,861	Mini ET (inert)	36,931
Total liftoff weight	4,438,785	Total liftoff weight	4,460,147

and a polymer that serves as both a binder and fuel. Inside each 0.5-in.-thick SRB steel casing, the propellant is shaped to reduce the thrust briefly at 62 s after liftoff during the critical period of transonic speed and maximum dynamic pressure. Burnout of the SRBs occurs a minute later, at an altitude of about 26.5 miles, and the empty casings are jettisoned and parachuted into the ocean, to be recovered and reused. The same procedure would be employed for the SRBs of the Mini STS.

The Shuttle ET is the primary structural element of the integrated Shuttle vehicle at launch, supporting the SRBs and the Orbiter. It consists of two propellant tanks connected by a cylindrical ring called the intertank, which distributes loads from the SRBs and provides structural continuity between the LOX tank and the LH2 tank. The smaller forward tank is filled with about 140,000 gal of LOX at a temperature of −233°F, which weighs 1,332,000 lb at launch. The larger rearward tank is filled with about 378,000 gal of LH2 at a temperature of −420°F, which weighs only 224,000 lb because liquid hydrogen is 16 times lighter than liquid oxygen. In contrast, the $\frac{3}{4}$-size Mini ET would hold about 129,000 gal of LOX weighing 1,226,800 lb in the forward tank and about 71,600 gal of RP-1 weighing 479,500 lb in the rearward tank. Thus, the total volume of liquid propellant is reduced from about 518,000 gal to about 200,600 gal, whereas the total liquid propellant weight is increased from 1,556,000 lb to about 1,706,000 lb. This increase in weight is balanced partly by the reduced weight of the Mini Orbiter and smaller payload and partly by a slightly larger total weight at liftoff.

Except for the payload, the listed weights of various components of the STS vehicle in Table 1 were obtained from published information. The payload weight was computed using the final value of mass fraction in orbit together with the Orbiter weight and the total liftoff weight. In the case of the Mini STS vehicle, the same procedure was used to determine the payload weight. However, the total weight of liquid propellant had to be computed first using the final value of mass fraction in orbit, subtracting the weight of solid propellant, and iterating to obtain the total liftoff weight. To determine the separate weights of RP-1 and LOX at liftoff, a fuel mass fraction of 0.281 was used (based on a mixture ratio of 2.56 for oxidizer mass to fuel mass). Note that the amount of RP-1 fuel required for the Mini Shuttle to reach orbital speed (71,600 gal) is not that much greater than the maximum fuel load of some long-range jet aircraft.

The Shuttle Orbiter has 49 rocket engines (including reaction control system jets); 23 antennas for communications, radar, and data links; 5 computers; separate sets of controls for flying in the atmosphere and in space; and electricity-producing fuel cells. It is about 122 ft long, 78 ft wide, and 57 ft high, and it weighs 160,000 lb empty. A $\frac{4}{5}$-size Mini Orbiter would be about 98 ft long, 62 ft wide, and 46 ft high and, ideally, would weigh about 89,000 lb empty. With a full load of consumables, it should weigh about 100,000 lb. The Shuttle Orbiter is designed to carry up to seven astronauts, four in the upper flight deck and three in the lower middeck. Depending on its role in the space program, the Mini Orbiter could be configured to carry up to five or more astronauts under slightly more cramped conditions and in an emergency or rescue situation.

Launch System Comparison

A comparison of several launch vehicles and their specifications is shown in Fig. 1 and Table 2. As mentioned earlier, the X-33 vehicle is a subscale prototype of the Lockheed Martin SSTO VentureStar

Table 2 Comparison of Space Shuttle specifications with those of Mini Shuttle and Lockheed Martin X-33/VentureStar vehicles

	STS	Mini STS	VentureStar	X-33
Length, ft	184	149	127	67
Width, ft	78	62	128	68
Gross liftoff weight, lb	4,439.000	4,460,000	2,186,000	273,000
Propellant	LH2/LO2 + solid	RP-1/LO2 + solid	LH2/LO2	LH2/LO2
Propellant weight, lb	3,776,600	3,926,900	1,929,000	211,000
Empty weight, lb	619,000	502,000	197,000	63,000
Main propulsion	Two solids + three SSMEs	Two solids + three MSMEs	Seven RS 2200	Two J-2S
Liftoff thrust	6,400,000	6,400,000	3,010,000	410.000
Maximum speed	Orbital	Orbital	Orbital	Mach 15+
Payload weight, lb	42,900	30,900	59,000	NA
Payload bay size, ft	15 × 60	12 × 48	15 × 45	5 × 10
Sea level specific impulse, s[a]	391	300	347	347
Vacuum specific impulse, s[a]	453	359	455	455

[a]Liquid rocket engine.

and is intended to be a technology demonstrator. Inasmuch as it is designed for suborbital operation, the ratio of structural weight to fully loaded weight is not critical. However, this is just the opposite with the VentureStar vehicle. According to its specifications, this SSTO vehicle will have an empty weight of 197,000 lb and a propellant load at liftoff of 1,929,000 lb. Assuming the same mixture ratio of 6 for oxidizer mass to fuel mass as used for the Shuttle's main engines, the volume of propellant tankage required is 638,220 gal. This is compared to the 518,000-gal capacity of the Shuttle's ET. It presents a very formidable, if not impossible, design problem then to build a practical spacecraft of such voluminous size that weighs only about 30% more than the Shuttle Orbiter. With consideration of these facts and other negative aspects, it is difficult to understand the arguments for feasibility presented by proponents of the SSTO concept.[2,3]

Conclusions

From a preliminary analysis for feasibility of a kerosene-fueled Mini Shuttle, it appears that this type of launch vehicle could be a practical solution to the problem of finding a worthy replacement for the Space Shuttle. Because no new technology is required, there would probably be greater safety and less risk than with other proposed systems such as the SSTO VentureStar. Moreover, the development time would be considerably shorter with greater assurance of meeting performance objectives. Although it is difficult to estimate precisely the reduction in launch costs with the Mini Shuttle, the savings should be substantial. With a $\frac{4}{5}$-size Orbiter, a $\frac{3}{4}$-size ET, and the same SRBs, the Mini Shuttle would have a payload capability about 75% of the Space Shuttle. Thus, there would seem to be sufficient justification for NASA to undertake an in-depth study of the merits of combining the Mini-Shuttle concept with that of the Shuttle II.

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Aerodynamic Flight Measurements and Rarefied-Flow Simulations of Mars Entry Vehicles

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Introduction

IN 1976, two Viking spacecraft successfully landed on Mars. The Viking Lander 1 touched down on the Martian surface (22.5°N, 48°W) about 4 p.m. local solar time on July 20, 1976, and later that year on Sept. 3, Viking Lander 2 landed (44°N, 226°W) about 10 a.m. local solar time. During entry, both vehicles traversed all of the speed regimes going from orbital velocities under near vacuum conditions, i.e., the free-molecule flow regime, through the hypersonic noncontinuum and continuum regimes, down to zero velocity on the planet's surface, where the pressure of the CO_2 atmosphere is less than 1% of the Earth's surface pressure. Because of the tenuous Martian atmosphere, a three-tier deceleration system (aerodynamic braking, drag magnification using a parachute, and finally terminal descent landing rockets) was used to place the Viking science payload on the surface of the planet. The Viking aerodynamic braking phase used a spherically blunted, 70-deg half-angle cone entry vehicle. Viking 1 was designated as the pathfinder for the second identical entry vehicle. Data collected from the first entry were quickly processed[1] and analyzed so that full advantage could be taken of the knowledge gained from the first Mars entry experience. This initial analysis was followed by more detailed analysis of the atmosphere[2] as well as vehicle performance.[3]

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