Mini/Micro Shuttles with Hypergolic Noncryogenic Liquid Rocket Bipropellant

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Introduction

MINI and Micro Shuttles are members of the hypothetical Space Shuttle family,[1] whose largest member is the Shuttle II (a second-generation Space Shuttle). One Shuttle II concept,[2] among several considered by NASA in its Access-to-Space study of 1993 is for a reconstituted, full-size Space Shuttle with essentially the same external tank (ET) and solid rocket boosters (SRBs) but having an orbiter upgraded with the latest technology and an improved thermal protection system.[3] Moreover, the Shuttle II would also incorporate a streamlining of systems to simplify ground operations so as to shorten the launch preparation time and lower costs.

The concept of a Space Shuttle family had its origin in the idea of downsizing the Shuttle Orbiter while replacing liquid hydrogen as fuel with kerosene (RP-1). This partial downsizing results in a slightly smaller version of the Shuttle (called a Mini Shuttle[4]) with a $\frac{3}{4}$-size orbiter and ET but the same size SRBs. For about the same liftoff weight as the full-size Shuttle, the Mini Shuttle has a payload capability about 75% as large in both size and weight. The Mini orbiter is still large enough for crewed missions with space for a crew of up to five and a payload bay measuring 12×48 ft. The three Space Shuttle main engines (SSMEs), producing 1.125×10^6 lb of thrust at sea level, could be replaced by a single, kerosene-fueled Russian RD-180 engine, which can be throttled from 37 to 100% of its rated thrust of 9.33×10^5 lb while remaining fixed in specific impulse.

Although the Mini Shuttle could prove to be less costly to operate than either the Space Shuttle or the Shuttle II, with a lower cost per pound of payload delivered to orbit, it is still a huge vehicle and larger than necessary for small-to-medium-size payloads (1,000–15,000 lb). To provide even lower payload-delivery costs, the size of the vehicle must be scaled to the size and weight of the payload. Thus, the Mini-Shuttle concept has been extended to obtain four successively smaller versions of the Mini Shuttle that are similar in function and shape but differ greatly in size and weight. These so-called Micro Shuttles[1] have payload capability commensurate with their total liftoff weight. Together with the Shuttle II and Mini Shuttle, they make up a proposed six-member Space Shuttle family. The orbiters in this family vary from full size down to $\frac{1}{5}$ size with the same planform loading so as to ensure having similar aerodynamic characteristics.

In the initial conception of Micro Shuttles as scaled-down derivatives of the kerosene-fueled Mini Shuttle, it was assumed that the bipropellant for the liquid rocket engines would be kerosene and liquid oxygen. However, because some potential applications of the Micro Shuttles require the ability to launch on short notice, it is highly desirable that both the fuel and the oxidizer be noncryogenic and storable. It is fortunate that there is such a bipropellant that is hypergolic (autoigniting) and able to yield a sufficiently high specific impulse to be considered a candidate for rocket use. It is, in fact, currently used by the Air Force in its Titan II, III, and IV space launch vehicles (SLVs).[5] Both the first and second stages of the Titan SLVs use Aerozine-50 as fuel and N2O4 (nitrogen tetroxide) as oxidizer. Aerozine-50 is a blend of 50% (by weight) unsymmetrical dimethyl hydrazine (UDMH) with 50% hydrazine. N2O4 contains about 30% nitrogen and 70% oxygen by weight. These propellants burn spontaneously when mixed, which eliminates the need for an igniter and improves the reliability of stage ignition. Because the propellants are storable, they can remain tanked in a launch-ready state for extended periods of time. Moreover, use of propellants storable at ambient temperature and pressure eliminates many of the handling problems associated with cryogenic liquids. In the case of Aerozine-50 and N2O4 the only problem in handling is to ensure that they do not come in contact and autoignite.

The purpose of this Note is to provide an analysis of feasibility for the use of noncryogenic liquid rocket bipropellant with semireusable launch vehicles such as the Mini and Micro Shuttles. In particular, the Note seeks to determine the amount of propellant required for each vehicle and to quantify the degradation in performance or payload capability when liquid oxygen (LOX)/RP-1 is replaced by N2O4/Aerozine-50. Even though there is a loss of about 12% in specific impulse by converting to this noncryogenic bipropellant, there is also an increase of about 15% in the propellant bulk density with a consequent reduction in tankage size and weight. Thus, it is important to provide specific documentation of the overall effects, in the case of a conceptual launch-vehicle design, of changing to a noncryogenic liquid rocket bipropellant.

Noncryogenic Liquid Rocket Bipropellant

The Titan family of SLVs, consisting of the Titan II, III, and IV, has a long history of successful use of storable liquid rocket bipropellant in both stages of the core component of each vehicle. For each stage the oxidizer (N2O4) and fuel (Aerozine-50) tanks are mounted in tandem with the oxidizer tank in front. Both tanks are pressurized on the ground with nitrogen and in flight with an autogenous pressurization system using cooled fuel-rich turbine exhaust gas for the fuel tank and vaporized N2O4 for the oxidizer tank. Because of the favorable storage characteristics of fuel and oxidizer, the Titan SLVs have an on-pad storage capability of 30 days fueled and (depending on the upper-stage propellant) are nearly ready to launch. However, because the bipropellant is hypergolic, extra precautions are in order when the launch-ready state is unduly prolonged to reduce the hazard of propellant mixing through tank leakage.

Among the nitrogen hydrides (compounds of nitrogen and hydrogen) only hydrazine (N_2H_4), monomethyl hydrazine (MMH), and UDMH have been used extensively as pure rocket fuels.[6] As is indicated in Table 1, hydrazine has a density and a range of temperature for the liquid state similar to that of water. Because of its higher density, higher performance (with any oxidizer), and lack of carbon, hydrazine would be preferred over the other fuels, but its high freezing point causes it to be unsuitable for use in most cases. However, a nominal $\frac{50}{50}$ mixture of hydrazine and UDMH produces the high-performance storable fuel known as Aerozine-50 with very few undesirable characteristics. Moreover, the cost of Aerozine-50 in large quantity is probably cheaper by far than that of any cryogenic fuel.

Among the many stable nitrogen oxides, nitrogen tetroxide (N_2O_4) or N2O4 is the most important rocket oxidizer because it has the highest oxygen content. As is indicated in Table 1, N2O4 has a density about 43% greater than that of water and about 25% greater than that of LOX. Although LOX gives higher performance with any fuel than N2O4 (due to its higher oxygen content), its cryogenic property makes it less suitable for certain applications where ease of handling and storability are critical. The tank for N2O4 does not require thick insulation and can be made of the same material (aluminum) as the tank for Aerozine-50. The 70°F boiling point of N2O4 is not a problem because it only contributes additional tank pressurization when the oxidizer reaches a higher temperature.

Effects of Changing Liquid Rocket Bipropellant

In converting from one liquid rocket bipropellant to another, the most significant changes are in the propellant bulk density and the specific impulse of the rocket propulsion system. A comparison of values of bulk density and specific impulse for three liquid rocket bipropellants is presented in Table 2. The three bipropellants are LOX/LH2, LOX/RP-1, and N2O4/Aerozine-50. The mixture ratios

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Table 1 Physical properties of hydrazine-based fuels and two liquid oxidizers

Property	Hydrazine	MMH	UDMH	Aerozine-50	LOX	N2O4
Formula	N_2H_4	$CH_3N_2H_3$	$(CH_3)_2NNH_2$	50/50 blend hydrazine/UDMH	O_2	N_2O_4
Specific density (relative to water)	1.004	0.874	0.785	0.899	1.144	1.434
Boiling point, °F	236	190	146	158	−297	70
Freezing point, °F	35	−62	−71	19	−361	12

Table 2 Values of bulk density and specific impulse for three liquid rocket bipropellants

Bipropellant oxidizer/fuel	Mixture ratio, (oxidizer mass)/(fuel mass)	Fuel mass fraction[a]	Density, lb/ft^3 oxidizer/fuel	Bulk density,[b] lb/ft^3	Specific impulse I_{sp}, s	
					Sea level	Vacuum
LOX/LH2	6.0	0.143	71.42/4.43	22.60	391	456
LOX/RP-1	2.3	0.303	71.42/50.32	63.37	300	359
N2O4/Aerozine-50	1.8	0.357	89.53/56.12	73.84	270	316

[a]Fuel mass fraction = (fuel mass)/(fuel mass + oxidizer mass) = 1/(1 + mixture ratio).
[b]Bulk density = (fuel mass + oxidizer mass)/(fuel volume + oxidizer volume) = 1/[(fuel mass fraction)/(fuel density) + (oxidizer mass fraction)/(oxidizer density)].

Table 3 Effects of changing liquid rocket bipropellant for Shuttle on size and weight of Orbiter, ET, and payload when SRBs are fixed in size and weight

Bipropellant oxidizer/fuel	(Mass in orbit)/(total liftoff mass)	Weight[a] of total mass in orbit, lb	Orbiter liftoff weight, lb	Payload weight, lb	SF		
					Orbiter	ET	SRBs
LOX/LH2	0.050066	222,196	180,000	42,196	1.000	1.000	1.000
LOX/RP-1	0.030491	135,321	101,250	34,071	0.750	0.750	1.000
N2O4/Aerozine-50	0.023427	103,971	80,000	23,971	0.667	0.674	1.000

[a]Assuming total liftoff weight = 4,438,066 lb.

shown are typical for each bipropellant because they are equal or close to those used, respectively, for the Space Shuttle, the Atlas and Delta first stages, and the Titan first and second stages.[5] Thus, the values of bulk density obtained are realistic for these bipropellants. Because the bulk density of LOX/LH2 is about 35% of that for LOX/RP-1, the volume of liquid propellant tankage for the kerosene-fueled 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 total weight of liquid bipropellant required for the Mini Shuttle with reduced payload is only about 10% more than that required for the Space Shuttle, and a reduction in ET volume to about 42% of that for the full-size ET is adequate. This would be the size of the ET if all dimensions were reduced by a scaling factor of 0.75. A $\frac{3}{4}$-size ET would have about half the external area and less than half the inert weight of the full-size ET. The reductions in size and inert weight of both the ET and the Orbiter, along with a payload reduction from 42,000 to 34,000 lb, are essential changes to compensate for the reduction of about 23% in specific impulse due to converting from LH2 to the lower energy fuel, RP-1.

In converting the liquid rocket bipropellant of the Mini Shuttle from LOX/RP-1 to N2O4/Aerozine-50, there is an increase of about 15% in bulk density of the bipropellant along with a further reduction of about 11% in specific impulse of the liquid rocket propulsion system. The effects of these changes are to require that the Mini Orbiter and ET be further reduced from $\frac{3}{4}$ size to about $\frac{2}{3}$ size and that the payload weight be reduced from 34,000 to about 24,000 lb, as is indicated in Table 3. (The Mini Shuttle, by definition, is a downsized Space Shuttle using noncryogenic fuel with smaller Orbiter, ET, and payload but having full-size SRBs.) The key mass-ratio results presented in Table 3 were obtained using a stepwise analytical method devised by the author for determining the motion and mass loss of a staged vehicle during vertical launch into orbit. In obtaining the ratio of mass in orbit to total liftoff mass for the three different liquid rocket bipropellants, 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, 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 Shuttle launch with the SRBs

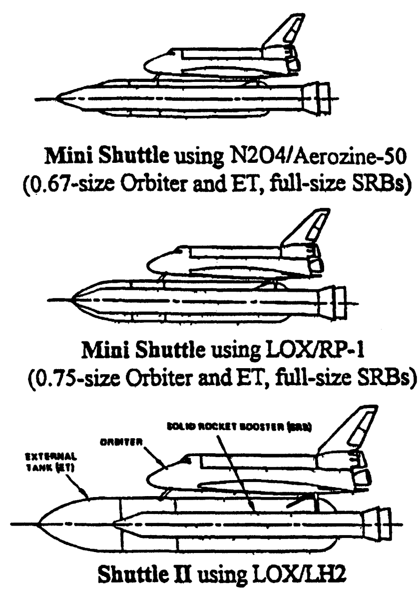

Fig. 1 Relative size of Shuttlelike vehicles using three different liquid rocket bipropellants.

jettisoned after burnout at 120 s after liftoff and the ET jettisoned after shutdown of the SSMEs at about 480 s.

An idea of the relative size of the two Mini Shuttle vehicles in comparison to the Space Shuttle or Shuttle II may be gained from the drawings to one scale shown in Fig. 1. The overall dimensions of each vehicle, along with the scale factors (SFs) and dimensions of its components, are listed in Table 4. It was assumed that the dimensions of the Shuttle II would be the same as those for the Space Shuttle, which were used to obtain the dimensions of the two Mini Shuttles and their components. In addition to specifying dimensions, the weights of the various masses of components and propellants at liftoff are also listed in Table 4 along with nominal thrust requirements. It is reasonable to assume that the hydrogen-fueled Shuttle II could use three of the same liquid rocket engines as the Space Shuttle

Table 4 Component dimensions (feet) and weights (pounds) along with thrust requirements (pounds) for various vehicles in the Space Shuttle family using N2O4/Aerozine-50 or LOX/RP-1[a] as liquid rocket bipropellant (Shuttle II uses LOX/LH2)

Component	Shuttle II full-size Orbiter	Mini Shuttle $\frac{2}{3}$-size, $\frac{3}{4}$-size*[a] Orbiter	Micro Shuttles			
			$\frac{1}{2}$-size Orbiter	$\frac{1}{3}$-size Orbiter	$\frac{1}{4}$-size Orbiter	$\frac{1}{5}$-size Orbiter
Orbiter (SF)		(0.667), (0.750)*	(0.500), (0.500)*	(0.333), (0.333)*	(0.250), (0.250)*	(0.200), (0.200)*
Total length	122.0	81.3, 91.5*	61.0, 61.0*	40.7, 40.7*	30.5, 30.5*	24.4, 24.4*
Wing span	78.1	52.1, 58.6*	39.1, 39.1*	26.0, 26.0*	19.5, 19.5*	15.6, 15.6*
Payload bay	15 × 60	10 × 40, 11.25 × 45*	7.5 × 30	5 × 20	3.75 × 15	3 × 12
External tank (SF)		(0.674), (0.750)*	(0.556), (0.572)*	(0.425), (0.437)*	(0.350), (0.361)*	(0.302), (0.311)*
Length	14.2	103.9, 115.6*	85.8, 88.3*	65.5, 67.4*	54.0, 55.6*	46.6, 47.7*
Diameter	27.5	18.5, 20.6*	15.3, 15.7*	11.7, 12.0*	9.6, 9.9*	8.3, 8.5*
SRBs (SF)		(1.000), (1.000)*	(0.825), (0.763)*	(0.630), (0.582)*	(0.520), (0.481)*	(0.448), (0.414)*
Length	149.2	149.2, 149.2*	123.2, 113.9*	94.0, 86.9*	77.6, 71.7*	66.9, 61.8*
Diameter	12.2	12.2, 12.2*	10.1, 9.3*	7.7, 7.1*	6.3, 5.9*	5.5, 5.1*
Whole vehicle						
Overall length	184.2	149.2, 149.2*	123.2, 113.9*	94.0, 86.9*	77.6, 71.7*	66.9, 61.8*
Overall width	78.1	52.1, 58.6*	39.1, 39.1*	26.0, 26.0*	19.5, 19.5*	15.6, 15.6*
Orbiter liftoff weight	180,000	80,000 101,250*	45,000 45,000*	20,000 20,000*	11,250 11,250*	7,200 7,200*
Payload weight	42,196	23,971 34,071*	13,484 15,143*	5,993 6,730*	3,371 3,786*	2,157 2,423*
SRBs (inert) weight	365,430	365,430 365,430*	205,554 162,413*	91,358 72,184*	51,389 40,603*	32,889 25,986*
Solid propellant weight	2,220,580	2,220,580 2,220,580*	1,249,076 986,924*	555,145 438,565*	312,269 246,731*	199,852 157,908*
ET (inert) weight	73,860	22,605 31,160*	12,715 13,849*	5,651 6,155*	3,179 3,462*	2,034 2,216*
Oxidizer weight	1,332,000	1,109,484 1,174,795*	624,085 522,131*	277,371 232,051*	156,021 130,533*	99,854 83,541*
Fuel weight	224,000	615,996 510,780*	346,498 227,014*	153,999 100,892*	86,624 56,753*	55,440 36,322*
Total liftoff weight	4,438,066	4,438,066 4,438,066*	2,496,412 1,972,474*	1,109,517 876,655*	624,103 493,118*	399,426 315,596*
Orbiter main engines						
Sea level thrust	1,125,000	932K, 932K*	524K, 419K*	233K, 186K*	131K, 105K*	84K, 67K*
Vacuum thrust	1,410,000	1,170K, 1,170K*	658K, 527K*	293K, 234K*	165K, 132K*	105K, 84K*
SRBs						
Sea level thrust	5,800,000	5,800K, 5,800K*	3,263K, 2,610K*	1,450K, 1,160K*	816K, 653K*	522K, 418K*
Average thrust	4,600,000	4,600K, 4,600K*	2,588K, 2,070K*	1,150K, 920K*	647K, 518K*	414K, 331K*
Whole vehicle at liftoff						
Total thrust	6,925,000	6.732K, 6,732K*	3,787K, 3,029K*	1,683K, 1,346K*	947K, 757K*	606K, 485K*
Thrust-to-weight ratio	1.56	1.52, 1.52*	1.52, 1.52*	1.52, 1.52*	1.52, 1.52*	1.52, 1.52*

[a]Asterisk denotes LOX/RP-1.

and that the kerosene-fueled Mini Shuttle could use a single Russian RD-180 engine or several smaller liquid rocket engines with nearly the same value of specific impulse. The Aerozine-50-fueled Mini Shuttle could probably use two of the same (or similar) Aerojet TechSystems LR87-AJ-11 liquid rocket engines (each of 274,000 lb of average thrust) that are used in the first stage of the Titan III SLV.[5]

Sizing of Micro Shuttles

The Micro Shuttles are downsized versions of the Mini Shuttle with the same liquid rocket bipropellant. However, rather than fix the size of the SRBs, the sizes or SFs of the Micro Orbiters are arbitrarily specified. The bases for scaling these smaller vehicles in the Space Shuttle family when the bipropellant is N2O4/Aerozine-50 are the same as when it is LOX/RP-1: 1) The fractions of total liftoff weight for each of four components (Orbiter, payload, ET, and SRBs) are the same as the component fractions for the similarly fueled Mini Shuttle. 2) The planform loading is the same for all of the Orbiters in the family (including the Shuttle II and Mini Shuttles) so that the Orbiter weight or mass m is proportional to the square of its size or SF with $m_2/m_1 = (\mathrm{SF})^2$. 3) The cubic scaling law is used to determine the separate and distinct SFs for sizing the ET and SRBs of each vehicle. The cubic scaling law infers that the mass ratio of similarly shaped vehicle components of the same average density (such as the ET and SRBs) is given by the cube of the SF. If m is the component mass, then $m_2/m_1 = (\mathrm{SF})^3$. Another way of saying this is that in shrinking the size of a vehicle component (ET or SRB), so that all dimensions are reduced by SF (with the average density held fixed), the mass of the smaller component is equal to the mass of the larger component times the SF cubed. Conversely, to determine the SF required to achieve a desired mass ratio, it is necessary to find the cube root of the mass ratio, so that $\mathrm{SF} = (m_2/m_1)^{1/3}$.

In arbitrarily stipulating nominal sizes or SFs of the various Micro Orbiters ($\frac{1}{2}, \frac{1}{3}, \frac{1}{4}, \frac{1}{5}$), it is a relatively simple matter to determine their weights according to the second basis and the weight of the Mini Orbiter. These resulting weights are such as to maintain the same value of planform loading and ensure that the various-size Micro Orbiters have similar aerodynamic characteristics. This requires that the average Orbiter density must increase as the size decreases (in conformity with the natural tendency of aircraft and spacecraft when reduced in size). Then, according to the first basis for scaling, the payload weight in each case is in the same proportion as that for the Mini Shuttle, as are also the propellant weights and the empty weights of the ET and SRBs. The final step in the sizing process, after obtaining the various component weights, is to determine the separate SFs for the ET and SRBs in each case, according to the cubic scaling law. (The SFs for the different size ETs are found by multiplying the SRB SFs by the SF for the Mini ET.) With these SFs, the dimensions of the ETs and SRBs, as presented in Table 4, are readily obtained.

In scaling the Micro Shuttles, by simply downsizing the ET and SRBs of the Mini Shuttle, and keeping the Orbiter and payload weights also in the same proportion, the same fraction of liftoff weight for propellant is maintained. Thus, there is assurance that each different-size vehicle will have sufficient solid and liquid propellant to attain orbital speed. From the nominal thrust requirements listed in the lower part of Table 4, it appears that the first- and second-stage liquid rocket engines of the Tital II and III SLVs would be suitable, in various combinations, for the Aerozine-50-fueled

Micro Shuttles. These Aerojet TechSystems engines, with designations LR87-AJ-11 and LR91-AJ-11, yield specific impulse values of 302 and 316 s, respectively. However, it would probably be desirable to modify the engines, in most cases, to provide throttling capability.

Conclusions

The use of Aerozine-50 as fuel and N2O4 as oxidizer for the liquid rocket engines of the Mini and Micro Shuttles in the Space Shuttle family appears to be entirely feasible. Although the performance (or specific impulse) of this autoigniting, noncryogenic bipropellant is lower than that of LOX/RP-1, it is sufficiently high to be considered in certain applications of semireusable launch vehicles where ease of handling and storability may be critical. The Mini Shuttle using LOX/RP-1 (with $\frac{3}{4}$-size Orbiter and ET and full-size SRBs) can deliver a payload of 34,000 lb to low Earth orbit, whereas the Mini Shuttle using N2O4/Aerozine-50 (with $\frac{2}{3}$-size Orbiter and ET and full-size SRBs) can only deliver a payload of about 24,000 lb. In the case of the smaller Micro Shuttles (with fixed sizes of Orbiter), the payload capability when using N2O4/Aerozine-50 (with slightly larger SRBs and higher liftoff weight) is 89% of that when using LOX/RP-1 (with slightly smaller SRBs and lower liftoff weight). However, in some military and space-rescue applications, where quick response is necessary, the use of a storable bipropellant may be preferable to use of a cryogenic fuel and/or oxidizer that provides greater payload capability. Thus, there is reason for the Department of Defense and NASA to consider use of Micro Shuttles with noncryogenic bipropellants and proven technology in their current or future programs to develop a practical military spaceplane for the Air Force and a safe and reliable, launch-ready crew-return/resupply vehicle for the International Space Station.

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Errata

Near-Polar Satellite Constellations for Continuous Global Coverage

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BECAUSE of an editing error, columns 4–5 and 10–11 in Table A1 should have the symbol "θ" instead of "μ". AIAA regrets the error.