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Launch Vehicle Performance Using Metallized Propellants

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Gelled metallized propellants provide options for increasing the performance of future launch vehicle chemical propulsion systems by increasing fuel density or specific impulse I_{sp}, or both. These increases in density and I_{sp} can significantly increase the payload, reduce the propulsion system liftoff weight, and allow a liquid rocket booster (LRB) to fit into the same volume as a solid rocket booster. As design examples, metallized propellant propulsion systems are considered as replacements for the solid rocket boosters and liquid sustainer stages on the current launch vehicles: both the Space Transportation System (STS) and the Titan IV. These vehicles are considered as examples to understand the real-world integration issues with future vehicles. Propulsion system mass-scaling equations and rocket engine performance predictions are used to estimate the size reductions of the high-density metallized boosters and some of the issues that must be considered before applying these fuels to future boosters are reviewed. A payload increase of 14–35% was enabled for the STS example using O_2/RP-1/Al and NTO/MMH/Al, respectively, while keeping an LRB within the dimensions of the SRB. No tank volume reduction or payload benefit was enabled with O_2/H_2/Al for the Space Shuttle Main Engine. A 11.2–11.6% payload increase for a Titan IV example was possible with NTO/MMH/Al propellants.

Nomenclature

A, B	=	dry mass parameters
I_{sp}	=	specific impulse, s
ML	=	metal loading, fraction of fuel mass
m_{dry}	=	dry mass
m_p	=	propellant mass
T	=	combustion temperature
ΔV	=	velocity change, m/s
ε	=	I_{sp} efficiency
ρ_m	=	density of metal in the fuel, kg/m^3
ρ_p	=	density of nonmetallized fuel, kg/m^3
$\rho_{p,m}$	=	density of metallized fuel, kg/m^3

Introduction

FUTURE improved launch vehicles will deliver larger, more massive payloads to orbit. Existing launch vehicles will also require continuing performance upgrades to accommodate the increasing national payload needs. The competition with international space launch services has also led commercial launch vehicle manufacturers to increase the payload capability of their future designs.[1] The NASA and Air Force plans for vehicles to low earth orbit (LEO) have assessed both small launch vehicles with 4536-kg payloads as well as much larger vehicles with payloads up to 113,400 kg.[2-7] While current plans for new launchers are focusing on 9072–18,144 kg to LEO,[8] a vigorous and expanded use of space (such as industrialization) will almost necessitate very large Saturn V class payloads.[9,10]

As payload mass increases, the propellant needed also rises and leads to larger and larger stage volumes. To deliver the higher payload masses to orbit within an acceptable size, higher I_{sp} rocket engines and higher density propellants will be desirable. Potentially, one of the most attractive liquid propellant options is metallized propellants. As an example of the benefits of these propellants, liquid rocket boosters (LRB) for the Space Transportation System (STS) were analyzed as replacements for the current solid rocket boosters (SRB). A replacement for the Space Shuttle Main Engines (SSME) using metallized oxygen/hydrogen/aluminum (O_2/H_2/Al) was also studied. The liquid stages of the Titan IV were also investigated using metallized Aerozine-50/aluminum (A-50/Al) fuel.

Background

Metallized propellants offer increases in the overall propellant density and/or the I_{sp} of a propulsion system. While increased I_{sp} reduces the required propellant and tank mass, the increases in propellant density can further reduce the tankage volume and mass. These gelled propellants have metal particles added to the fuel or the oxidizer. Typically, the metal is in the form of micron-sized particles and they are suspended in the gelled liquid propellant. Many previous mission analysis studies[11-16] have determined that metallized propellants are an attractive alternative to traditional propellants for future STSs.

With metallized propellants, there is also an added safety advantage in handling. Because the fuel is gelled, it prevents widespread spillage if it were released from the propellant tank.[17] Cleanup of the spill is easier because the spill is restricted to a more confined area. This is particularly true of monomethyl hydrazine/aluminum (MMH/Al) and rocket propellant-1/aluminum (RP-1/Al) metallized fuels. Also, the gel makes the propellants less sensitive to high-energy particles that penetrate the propellant tank.[17] If a projectile penetrates the tank (such as a wrench dropped during ground assembly, micrometeoroids, space debris, etc.), the gelled propellant will prevent a catastrophic explosion.

Propulsion Systems Analyses

In the analyses presented here, several figures of merit are considered. These are the payload delivery mass to an Earth orbit, the length, diameter, or the volume of the vehicle, and the gross lift off weight (GLOW).

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Launch Vehicle Design Constraints

In the analyses of the STS performance, the Ulysses launch mission parameters were used as a guide.[18,19] The total payload mass delivered to orbit was 22,527 kg. This mass includes 20,873 kg of payload and 1654 kg of Manager's Reserves (or payload contingency[18]). The baseline payload to orbit for the Titan IV was 14,643 kg.

Propulsion System Design

For the STS LRBs, both pump- and pressure-fed boosters were analyzed. All of the remaining engine designs for the STS SSME and Titan stages' engines are pump-fed. Some of the design parameters for the engines were guided by the results of the previous LRB studies.

Engine Performance

Using a computer simulation code,[20] the engine performance of the metallized propellant combinations was estimated. The engine efficiencies were derived using the performance estimates from liquid engine systems[14,15,21–23] and comparisons with the vacuum I_{sp} predicted by the engine code. A wide range of metal loadings were considered for $O_2/H_2/Al$, O_2/RP-1/Al, and nitrogen tetroxide/monomethy hydrazine/aluminum (NTO/MMH/Al), and two-phase flow and other losses in metallized engines were analyzed. Figure 1 shows the effect of metal loading on I_{sp} for O_2/RP-1/Al, NTO/MMH/Al, and $O_2/H_2/Al$. The I_{sp} was not always a strong function of the metal loadings for each combination. The highest I_{sp} points for the three propellant combinations were 65% in $O_2/H_2/Al$ (for the SSME), 5–10% in O_2/RP-1/Al, and 40% in NTO/MMH/Al.

ENGINE MIXTURE RATIOS

METAL LOADING	NTO/MMH/AL LRB	O_2/RP-1/Al LRB	$O_2/H_2/Al$ LRB	$O_2/H_2/Al$ SSME
5.0	-	2.6	-	-
10.0	-	2.4	-	-
15.0	-	-	-	-
20.0	-	-	-	-
25.0	-	-	-	-
30.0	1.3	1.7	2.8	-
35.0	1.0	1.5	2.5	-
40.0	0.9	1.4	2.0	2.5
45.0	0.9	1.3	1.8	2.2
50.0	0.9	1.2	1.6	1.8
55.0	1.0	1.1	1.2	1.5
60.0	1.0	1.1	0.9	1.1
65.0	-	-	-	0.7
70.0	-	-	-	0.8
EXPANSION RATIO:	30:1	30:1	30:1	77.5:1

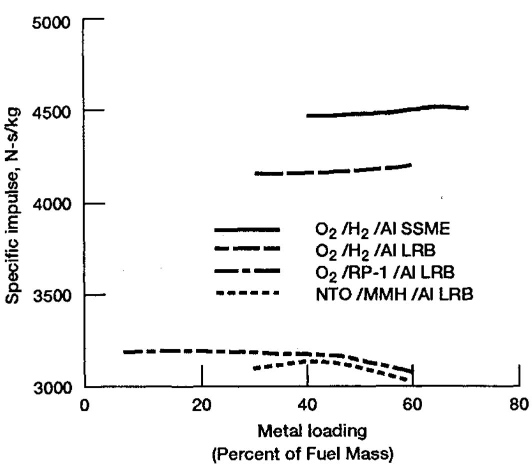

Fig. 1 Specific impulse vs metal loading.

Table 1 provides the "best" I_{sp} values, and Table 2 lists the metal loadings and mixture ratios. The best design was based on the vehicle design constraints, such as volume available for the LRB or other booster volume, and not the maximal I_{sp}. The NTO/MMH/Al systems were able to deliver the highest I_{sp} increases over the nonmetallized cases. With the pump-fed LRB, the I_{sp} had risen 11.2 s. Also, the NTO/A-50/Al propellants for the Titan IV provided a 9.2-s I_{sp} rise for Stage 1 and a 14-s increase for Stage 2. The Titan engine performance using metallized NTO/A-50/Al required a metal loading of 35–40% to produce the maximum I_{sp} increase for these engines.

An important point to note is that the metallized cases with O_2/RP-1/Al had a net I_{sp} reduction over the nonmetallized O_2/RP-1 combination. A small I_{sp} drop also occurred with the pressure-fed NTO/MMH/Al system. Although the I_{sp} was lowered with the addition of the metal, the density increase

Table 1 Nonmetallized and metallized engine performance

Vehicle and propellant	I_{sp}, s No metal	I_{sp}, s Metal[a]	I_{sp} efficiency, η
STS: booster options—pump-fed			
SRB	265.5	n/a	n/a
O_2/RP-1	324.5	317.3	0.920
NTO/MMH	307.7	318.9	0.920
O_2/H_2	419.2	428.2	0.940
Pressure-fed			
O_2/RP-1	289.4	284.8	0.920
NTO/MMH	280.4	278.3	0.920
Main propulsion options			
O_2/H_2	452.66	460.6	0.974
Titan IV			
Stage 1 options			
NTO/A-50	301.0	310.2	0.914
Stage 2 options			
NTO/A-50	316.0	330.0	0.906

[a]Aluminum is added to the fuel.

Table 2 Rocket engine metal loadings and mixture ratios

Vehicle and propellant	Metal loading, %	Mixture ratio Metal	Mixture ratio No metal
STS: booster options—pump-fed			
O_2/RP-1	55	1.1	2.7
NTO/MMH	40	0.9	2.0
O_2/H_2	60	0.9	6.0
Pressure-fed			
O_2/RP-1	55	1.1	2.5
NTO/MMH	50	1.0	2.0
Main propulsion options			
O_2/H_2	70	0.8	6.0
Titan IV			
Stage 1 options			
NTO/A-50	35	0.69	1.91
Stage 2 options			
NTO/A-50	40	0.68	1.78

Metal loading = percent of fuel mass.

afforded with the 55% Al loading enables denser packaging of the booster and a payload-to-orbit gain, even with a reduction in I_{sp}.

The maximal metal loading considered for $O_2/H_2/Al$ was 70% of the fuel mass. The metal loading when considering all of the propellant (oxidizer and fuel) of the $O_2/H_2/Al$ propulsion system was 38.9% (for a mixture ratio of 0.8 with a 70% Al loading). The $O_2/H_2/Al$ peak I_{sp} was 461.2 s at a metal loading of 65% of Al in the H_2/Al fuel, with an ε of 77.5:1 and a mixture ratio of 0.7.

Propellant Density

Using the aluminum loadings considered in the engine performance calculations, the propellant density for the RP-1 was increased from 773 to 1281 kg/m^3 (55% Al loading in the fuel). For H_2 fuel, the density increased from 70 to 220.3 kg/m^3 (H_2 with a 70% Al loading). The density increase was computed using

$$\rho_{p,m} = 1/[(1 - ML)/\rho_p + ML/\rho_m]$$

Mass Scaling Equations

In determining the dry mass of the launch vehicle stages, the following general mass-scaling equation was used:

$$m_{dry} = A + Bm_p$$

Table 3 lists the propulsion mass-scaling parameters for all of the considered systems. These parameters address all of the masses that are required to store and deliver propellants to the main engines. They include tankage, engines, feed system, thermal control, structure, residuals, and contingency.[24] Also included, if needed, are the aerodynamic structure of the boosters, such as the nose cone and aft skirt of the LRB. These parameters were derived from the results of the LRB studies and the results of propellant-tank mass estimation codes used in previous studies.[2,11,12,16] The parameter A of the scaling equations varied due to the different engine, nose cone, and aft skirt masses of the differing boosters. The B parameter is dependent upon the propellant mixture ratios, the propellant metal loading and, hence, the propellant density.

Table 3 Propulsion system mass-scaling parameters: dry mass per booster

Vehicle and propellant	Scaling parameters A	B
STS: booster options		
Solid	85,698.8	0.0
Pump-fed		
O_2/RP-1	26,184.8	0.0747
O_2/RP-1/Al	26,261.2	0.0715
NTO/MMH	26,294.4	0.0650
NTO/MMH/Al	26,294.4	0.0642
O_2/H_2	26,236.9	0.0925
$O_2/H_2/Al$	26,236.9	0.1016
Pressure-fed		
O_2/RP-1	30,456.9	0.2009
O_2/RP-1/Al	30,456.9	0.1767
NTO/MMH	29,737.2	0.1463
NTO/MMH/Al	29,737.2	0.1332
Main propulsion options		
O_2/H_2	36,050.1	0.0
$O_2/H_2/Al$	10,517.4	0.0469
Titan IV		
Stage 1 options		
NTO/A-50	9,235.2	0.0
Stage 2 options		
NTO/A-50	4,137.3	0.0

Mission Analysis

On the STS missions, the Orbiter is placed in a 296-km (160-n.mi.) circular orbit with a 28.5-deg inclination, representative of a launch from the Kennedy Space Center. With the Titan IV, the final payload was placed in a circular orbit with a 407-km (220-n.mi.) altitude and an inclination of 28.5 deg. Additional details of the mission design and analysis codes are provided in Refs. 24 and 25.

Results

Space Transportation System

LRB for SRB Replacement

O_2/RP-1/Al LRB. The replacement of the SRB with O_2/RP-1/Al allowed denser packaging of the booster within the SRB dimensions. Figure 2 contrasts the pump-fed LRB length and diameter. If the booster was constrained to the diameter of the SRB, the O_2/RP-1/Al booster was 43.4 m long, 2 m shorter than the SRB. Using O_2/RP-1, the pump-fed booster was 47.6 m long; this length exceeded the 45.4-m SRB length.

Because the metallized LRB was smaller than the existing SRB, the sensitivity of booster size to payload-to-orbit was considered. In Fig. 2, the LRB lengths are compared for four payload masses. Using a metal loading of 55% in the O_2/RP-1/Al LRB allowed the booster to fit within the existing SRB diameter and length, and deliver 25,674 kg (56,600 lbm) of payload. By allowing the LRB length to increase to 49.3 m, the payload to orbit was increased to 31,979 kg (70,500 lbm). This was a 42% payload increase over the STS-with-SRB payload capability. While these lengths violated the strict SRB length, these results were included to show the potential payload advantages of longer metallized LRBs.

A pressure-fed O_2/RP-1/Al LRB was also investigated. The length and diameter of these boosters were not compatible with the SRB constraints. The metallized LRB was, however, substantially shorter than the nonmetallized booster. Figure 3 contrasts the pressure-fed boosters with the a 55% metal

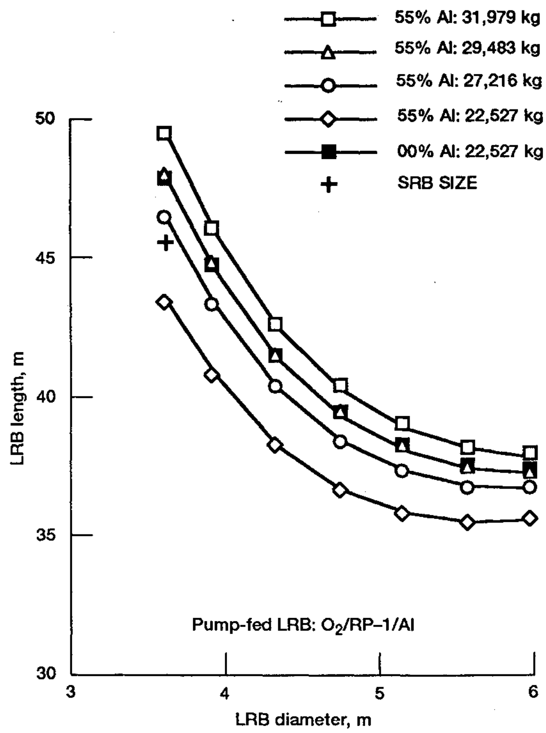

Fig. 2 LRB length vs diameter with O_2/RP-1/Al—payload mass parametrics.

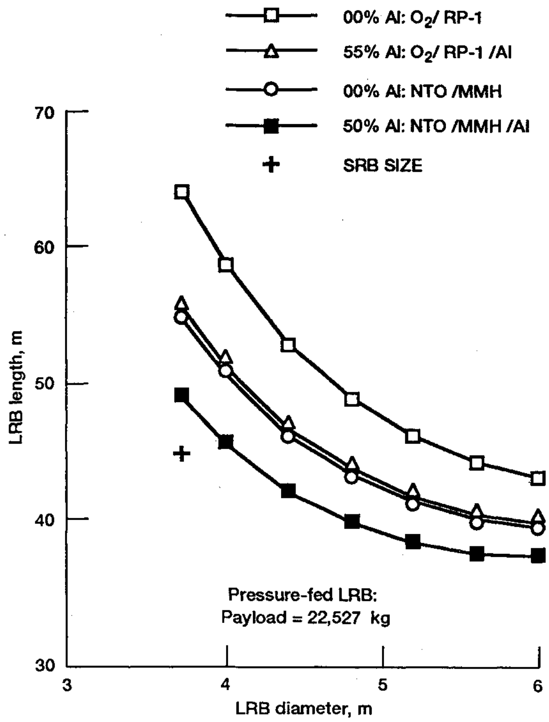

Fig. 3 LRB length vs diameter with pressure-fed booster.

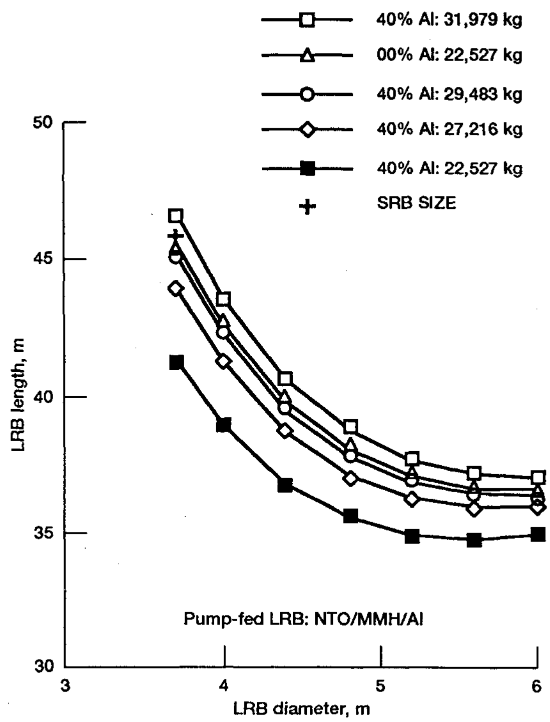

Fig. 4 LRB length vs diameter with NTO/MMH/Al—payload mass parametrics.

loading. The LRB length (when using the SRB diameter) was 56.3 m. The corresponding O_2/RP-1 LRB length was 65 m.

NTO/MMH/Al LRB. As with the O_2/RP-1/Al boosters, the higher density of the metallized pump-fed NTO/MMH/Al, depicted in Fig. 3, resulted in a very small LRB, only 40.8 m long, 4.6 m shorter than the SRB. The metal loading selected for the MMH was 40%. The pump-fed NTO/MMH/Al booster delivered a 31,979 kg (70,500 lbm) payload if the booster length was increased to 46.2 m; this was only 0.8 m over the existing SRB dimensions.

The length and diameter of a pressure-fed NTO/MMH/Al booster with a 50% metal loading is illustrated in Fig. 4. A higher metal loading than that for the pump-fed booster was used in this LRB to attempt to fit it within the SRB size. At this loading, the booster was unable to fit in the SRB length unless the LRB diameter was greater than 4 m. None of the pressure-fed LRBs fit the SRB volume constraint.

LRB Masses. Table 4 compares the O_2/RP-1/Al and NTO/MMH/Al LRB mass summaries. These boosters were sized for the baseline payload mission. Each of the boosters was substantially lighter than the SRB. The GLOW of these options was therefore lower than the standard STS-SRB vehicle. The O_2/RP-1/Al case reduced the GLOW by 19% (or 394,500 kg), and the NTO/MMH/Al case was able to reduce the GLOW by 20% (or 411,881 kg).

Specific Impulse Efficiency η Effects on LRB Length. The influence of η on the performance of the metallized launch vehicles was investigated. Due to the two-phase flow of the metallized propellants in the combustion chamber and nozzle, there is a difference between the gas and solid-liquid particle velocities, which creates a performance loss. The solid-liquid particles are composed of solid and liquid aluminum oxide (Al_2O_3). Once the potential losses of metallized propellants were introduced into the analysis, the performance was much lower than previously predicted.

O_2/RP-1/Al η Effects. Figure 5 provides the parametrics of LRB length and η for O_2/RP-1/Al propellants. In the figure, the metallized η is varied from 0.87 to 0.92. This range reflects the performance penalties that have been measured and predicted for metallized propellants, up to a 5% reduction in η.[26–30] The LRB length was 46 m with the worst-case η. Even with an η penalty of 4% (η = 0.88), the O_2/RP-1/Al LRB was able to fit within the SRB length requirement. This case is for the baseline payload of 22,527 kg.

NTO/MMH/Al η Effects. The overall effect of reduced η was least detrimental for NTO/MMH/Al propellants. Figure

Table 4 LRB mass summary: metallized O_2/RP-1/Al and NTO/MMH/Al propellants

	Mass, kg	
Subsystem	O_2/RP-1/Al	NTO/MMH/Al
Oxidizer tank	1,663.0	828.3
Fuel tank	1,349.0	1,125.2
Pressurization	1,106.5	91.3
Engines and feed system	19,538.9	19,538.9
Thermal control	3,421.8	3,363.1
Subsystems:	1,698.0	1,698.0
Avionics		
Separation system		
Power		
Structure	7,528.0	7,398.3
Nose cone	745.0	745.0
Residuals and holdup	5,211.0	5,121.3
Contingency, 20%	8,452.2	7,982.0
Total	50,713.4	47,891.9
Usable propellant	342,180.8	336,310.6
Total STS GLOW with LRB:	1,657,671.0	1,640,287.0

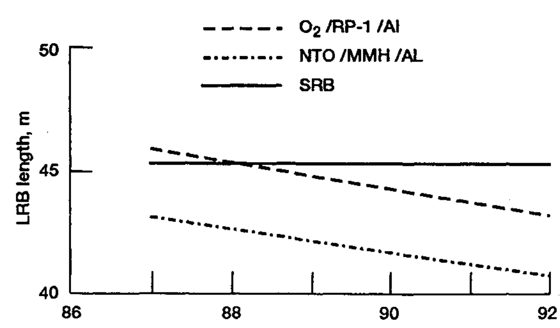

Fig. 5 LRB length vs I_{sp} efficiency.

5 provides the parametrics of booster length and η for NTO/MMH/Al. A η range of 0.87–0.92 was used. As discussed in the previous section, this range reflects the measured and predicted performance penalties for metallized propellants: up to a 5% reduction in η.[26–30] As with the results for O_2/RP-1/Al discussed above, the NTO/MMH/Al booster for the STS with the baseline 22,527-kg payload was able to fit within the SRB length and diameter. With the metallized NTO/MMH/Al for the baseline payload, the length was 43.2 m for the worst-case penalty of $\eta = 0.87$.

Clearly, the η had a very strong influence on reducing the LRB size in some of the metallized cases. This was especially true for the higher payload cases. A penalty of the magnitude predicted for metallized propellants will seriously reduce their benefits. Small reductions in the η, however, will be absorbed with only a small booster length increase. Research on reducing the losses associated with metallized systems has been conducted.[26–29] Reducing the Al_2O_3 particle size will reduce the gas and solid-liquid velocity differences and improve the metallized η. Engine simulations have shown that if only very small particle sizes are present in the exhaust (less than 1 μ), the engine η is close to the theoretical maximum. Current particle sizes in a metallized engine exhaust, however, are between 10–100 μ.[26–29] If future research is unsuccessful and metallized engines experience large η penalties, and cannot deliver added payload, there are still benefits to be gained. The increased safety offered by gelled metallized propellants and the controllability enabled with a liquid engine makes a metallized booster an important safety enhancement over solid propulsion.

$O_2/H_2/Al$ LRB. There was little volume benefit from the pump-fed O_2/H_2 or $O_2/H_2/Al$ LRB. This LRB was not able to meet the SRB sizing requirement. The length of the LRB without metallized propellants was 80.6 m. With metallized $O_2/H_2/Al$ (60% metal loading), the booster length was 96.3 m. This was substantially longer than the 45.4-m SRB length. The metallized booster length was equal to the SRB only at diameters much greater than 6.1 m. Thus, the O_2/H_2 and the $O_2/H_2/Al$ boosters were poor performers when using the SRB sizing constraints.

For pump-fed booster engines, the nozzle expansion ratio was small: 30:1. When using the low expansion ratios required for the $O_2/H_2/Al$ LRB engines, the maximum I_{sp} for the metallized propellants occurred at a low mixture ratio. This low mixture ratio forced the tank's total volume to be greater than that for the O_2/H_2 system at a 6:1 oxidizer to fuel ratio.

Main Propulsion System Replacement

The volume of the external tank (ET) using metallized $O_2/H_2/Al$ in the SSME is shown in Fig. 6. At a 70% Al loading, the I_{sp} was increased from 452.7 to 460.6 s. This metal loading was selected after analyzing a range of loadings from 40 to 70%. A 70% loading produced the smallest volume increase of the ET. Standard SRBs were used in this analysis. Two levels of contingency (or masses that are added to the ET dry mass due to design uncertainties) were used: 0 and 20%. The variation in contingency demonstrated the influence of the dry mass on performance, and the 20% contingency is representative of that used in preliminary design. A performance increase was enabled with metallized $O_2/H_2/Al$, but not without increasing the ET volume. With these propellants, the mixture ratio of the propulsion systems was very low: 0.8. As with the $O_2/H_2/Al$ LRB analysis, the volume of the metallized ET was larger than the standard ET. Because the mixture ratio of the $O_2/H_2/Al$ system (with 70% Al in H_2/Al) is so low, the tankage volume was increased by 8.7% over the ET for the baseline payload (0% contingency). Even with the increased density of the H_2/Al, the metallized system was not able to fit within the ET volume constraint.

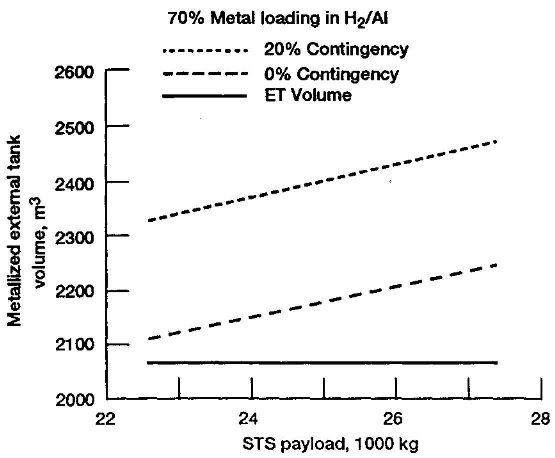

Fig. 6 Metallized ET volume vs payload.

Titan IV

In the Titan IV simulations, the total vehicle weight (launch vehicle minus the payload) remained constant. Thus, the vehicle dry mass and the total propellant loads for both the metallized and nonmetallized core stages were the same. No replacements of the SRMs were considered. Using metallized NTO/A-50/Al, the payload was increased from 14,643.0 to 16,336.3 kg (an increase of 11.6%). In a comparison where the GLOW of the two vehicles were equal, the Titan payload was increased to 16,286 kg, or 11.2% higher than the nonmetallized case. An analysis of the η effect on the Titan payload was not conducted. As with the LRB, even if the payload to orbit is not significantly increased, the added safety benefits of gelled propellants may be as important as potential payload increases.

To take advantage of metallized propellants, the Titan IV would have to have several major modifications. Though the same total propellant mass was used in each of the stages, the volumes of the oxidizer and the metallized A-50/Al fuel are different from those for the A-50 fuel. With the 0.68 mixture ratio for the metallized Titan first stage, the total propellant volume needed was 121.61 m^3. The volume available in the first stage was 126.72 m^3. However, the volume split of the oxidizer and fuel was incompatible with the existing tankage volumes. Therefore, the tank dome locations would have to be changed to accommodate the new propellants. The overall stage dimensions, however, were unchanged.

Also, the combustion temperature of the metallized Titan engines will be somewhat higher than the existing engines. For the first stage, the predicted metallized combustion temperatures (35% Al in A-50/Al) and the existing Titan engine temperatures were 3419 and 3336 K, respectively. Additional engine cooling and other modifications would be needed for the vehicle feed lines, propellant acquisition system, and the engine turbomachinery.[27,30]

Other Implementation Issues

Pump-Fed and Pressure-Fed Systems

With the very high I_{sp} systems being considered for launch vehicles, a pump-fed engine may be required. Pressure-fed propulsion systems are also under consideration, but they typically require larger masses for propellant tankage and pressurization systems. Currently, metallized propellants are fed to small propulsion systems with positive-displacement propellant expulsion devices (diaphragms, etc.[31,32]). A positive expulsion system, however, is considered impractical and too massive for large propellant tanks. Preliminary metallized fuel pump and propellant expulsion work was conducted in previous research programs.[27,33–34] This work demonstrated the feasibility of pumping metallized fuels. Although erosion of the pump components did occur, they were able to deliver propellants for the required time. Also, the research showed that very high expulsion efficiency could be achieved for metallized propellants without using positive-expulsion devices in the propellant tanks. It seems likely that metallized fuels are therefore adaptable to pump- or pressure-fed systems.

The design issues with gelled thixoptropic propellants, combustion efficiency, and engine cooling techniques are addressed in more detail in Ref. 30. Numerical modeling, propellant rheology experiments, and hot-fire engine testing have been conducted to determine the potential engine efficiency of metallized propellants.[26-35] While many of these issues have been researched for many years for military applications in tactical missiles and ejection seats[31,32] using gelled NTO or IRFNA with MMH/Al, there still remains much work to be done regarding O_2/RP-1/Al for space applications.

Concluding Remarks

Metallized propellants offer several options for the system designer looking for ways to improve future launch vehicles' payload capacity and safety. High-density metallized fuels play a critical role in allowing liquid propulsion systems to meet the demanding volume constraints of a solid rocket. Even though the I_{sp} of the O_2/RP-1/Al engine suffers a reduction over its nonmetallized counterpart, both these propellants and NTO/MMH/Al are able to enhance the Earth-to-Orbit vehicle payload capability while remaining within the solid rocket volume. Payload increases of 14–35% are enabled in the STS examples. With the Titan IV example, an 11.2–11.6% increase in the payload to LEO is enabled with metallized NTO/A-50/Al Earth-storable propellants. Alternatively, if no payload increase is desired, a significant volume savings is also possible by taking advantage of the higher density of the A-50/Al fuel. A vehicle using O_2/H_2/Al showed no volume reduction for the STS configuration when used in either the LRB or the ET.

Based on these potential volume savings and payload increases, future design studies of launch vehicle enhancements may, therefore, wish to include metallized propellants as a propulsion option. Though issues with engine two-phase flow losses can penalize metallized propellants' I_{sp}, their increased safety and density can offer important advantages. By offering the potential of increased I_{sp}, density, and safety, metallized propellants may provide the best of all propulsion's worlds.

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