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PRELIMINARY ASSESSMENT OF USING GELLED AND HYBRID PROPELLANT PROPULSION FOR VTOL/SSTO LAUNCH SYSTEMS

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Abstract

A novel, reusable, Vertical-Takeoff-and-Vertical-Takeoff-and-Landing, Single-Stage-to-Orbit (VTOL/SSTO) launch system concept, named AUGMENT-SSTO, is presented in this paper to help quantify the advantages of employing gelled and hybrid propellant propulsion system options for such applications. The launch vehicle system concept considered uses a highly coupled, main high performance liquid oxygen/liquid hydrogen (LO2/LH2) propulsion system, that is used only for launch, while a gelled or hybrid propellant propulsion system auxiliary propulsion system is used during final orbit insertion, major orbit maneuvering, and landing propulsive burn phases of flight. Using a gelled or hybrid propellant propulsion system for major orbit maneuver burns and landing has many advantages over conventional VTOL/SSTO concepts that use LO2/LH2 propulsion system(s) burns for all phases of flight. The applicability of three gelled propellant systems, O2/H2/Al, O2/RP-1/Al, and NTO/MMH/Al, and a state-of-the-art (SOA) hybrid propulsion system are examined in this study. Additionally, this paper addresses the applicability of a high performance gelled O2/H2 propulsion system to perform the primary, as well as the auxiliary propulsion system functions of the vehicle.

I. Introduction

Almost all U.S. launch systems, except for the Space Shuttle, are descendants of first generation intercontinental ballistic missiles of the early 1960's.

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They are costly and require weeks and even months of preparation for launch, and have little resilience to major subsystem operational failures. All of the modifications and upgrades incorporated since then are not able to overcome their limitations. None have an engine-out capability; that is, any engine failure occurring any time other than just before reaching orbit, even if not directly destructive, will cause loss of the payload, or place it in an unsuitable and probably useless orbit. All are expendable, except for the Space Shuttle, requiring not only replacement of all of the flight hardware and software for every mission, but also preventing any evolutionary improvement in reliability. Launch systems are unlike an aircraft, that can return and land with a bad engine, or faulty navigation system, and have a replacement installed. Additionally, all these launch systems require lengthy, labor-intensive, complex preparations for flight, involving many highly skilled workers, as well as needing extensive Ground Support Equipment (GSE). The limited margin associated with the Space Shuttle design requires that lengthy, pre-flight preparations be followed for each flight to ensure safe operation of the system. Present day launch systems require special efforts to accommodate all but the simplest payloads, and lengthy testing and checkout to assure proper cargo integration. This is in contrast to an air transport where operational availability and efficiency is inherently supported in its design.

Examining the air transport example can teach us what are the important characteristics of a truly economical space launch system. A launch vehicle should have an engine out survival capability with mission completion or safe return to the ground possible from anywhere in its flight trajectory, from launch to landing. It should be fully reusable, with turnaround between missions requiring a minimum of routine hardware and software servicing and checkout, followed by cargo loading, rapid refueling, crew checks (if manned) and launch. Such a system will achieve cost reductions as a consequence of the absence of most of the procedures which are costly in our present launch systems, including the Space Shuttle. It must also be equipped with a generic cargo hold with standard hold down fixtures, and have fully characterized launch and recovery environments published for users. The cargo will have to be designed and built to accept these environments, thereby obviating the need for any special analysis or provisions to allow it to fly on the launch vehicle. The preparations should not be anymore extensive than such preparations used for an air transport freighter. A VTOL/SSTO launch vehicle offers the possibility of having all of the characteristics described above. By its nature, such a system does not throw anything away, requires no elaborate prelaunch system integration, can be designed to require a small launch crew (if required), and have no gantry. It should also have the capability to be launched out of minimal inland launch facilities and be recovered at almost any large air field, such as a military air base.

VTOL/SSTO launch systems have been under study for many years. Past VTOL/SSTO concepts studied include the German MBB BETA vehicle, General Dynamic's NEXUS, the Boeing Big Orion, and the Douglas Pegasus, Romulus and Hyperion vehicles.[1] Current activities in this area include the recent DC-X (also known as Delta Clipper, Clipper Graham or DC-XA) flight demonstration program and the current X-33 program, as well as advanced launch vehicle technology demonstration programs under NASA and/or Air Force sponsorship.[2,3] Past studies characterized promising VTOL/SSTO vehicle concepts, which were all highly sensitive to propulsion performance and dry weight. Additionally, these vehicle concepts required designs that where highly integrated, when compared to present day launch systems that presented numerous engineering challenges. Recent technical advancements arising out of the National AeroSpace Plane (NASP), Air Force, Strategic Defense Initiative (SDI) and Ballistic Missile Defense Organization (BMDO) programs developments, the Advanced Launch System (ALS), the Space Shuttle and experimental aircraft programs such as the X-29 have addressed these technical issues and opened new opportunities.[3,4] Application of this technology base makes a low cost, responsive, reliable VTOL/SSTO launch vehicle a more viable option.

A preliminary design assessment study was undertaken recently to investigate a novel, fully-reusable VTOL/SSTO launch vehicle design and system approach with the potential to reduce payload to orbit costs, increase responsiveness through short turnaround time, and be economical to develop.[5] This vehicle design concept combined the use of a highly coupled, high performance LO2/LH2 main propulsion system with a hybrid system for auxiliary propulsion. SOA hybrid propulsion system technology was considered in this assessment.[5] In addition, high temperature, high strength-to-weight materials and thermal management techniques from the NASP program, and where possible, lightweight, highly robust, miniaturized subsystem technologies, such as for guidance, sensor, power, and computer subsystems, that were examined in past and present SDI/BMDO programs, were used in the design concept. It should be noted that this launch vehicle concept was originally conceived by Mr. William Haynes, and the authors wish to acknowledge him.[6] This launch system, named HYbrid Propulsion-Single-Stage-to-Orbit (HYP-SSTO), successfully addressed many of the propulsion performance, structural weight, and design integration issues, typical of such systems, in a much different way than they have been considered in past and present design approaches.[7]

The work reported in this paper expands on the past HYP-SSTO concept assessment work.[7] This work reassessed the applicability of employing a SOA hybrid propulsion as a VTOL/SSTO augmentation (or auxiliary) propulsion system (APS). Additionally, much of this study effort also focused on assessing the feasibility of candidate O2/H2/Al, O2/RP-1/Al, and NTO/MMH/Al gelled propellant propulsion systems to perform the VTOL/SSTO APS function. This new VTOL/SSTO system concept, which can include a hybrid or gelled propellant APS, is named AUGMENTed- propulsion-Single-Stage-to-Orbit, AUGMENT-SSTO. Gelled propellant propulsion systems exhibit many of the system design and operational integration features that are typical of a hybrid-propellant VTOL/SSTO APS, while operating at a higher specific impulse (Isp). Thus, a gelled VTOL/SSTO APS has the potential to display payload vehicle system performance approaching that characteristic of classic VTOL/SSTO launch systems which use SOA LO2/LH2 propulsion systems to perform all the required major propulsion firing functions. Because gelled and hybrid propellant propulsion systems are inert by their nature, such launch system concepts also have the potential to support short turnaround times between launches and reduce (or provide a competitive) overall system life-cycle cost. This work also examined the applicability of a high performance gelled O2/H2/Al propulsion system to perform the main propulsion system (MPS) function, as well as the auxiliary propulsion system functions of the vehicle. In addition to considering performance issues associated with a VTOL/SSTO that uses a gelled O2/H2/Al propulsion system for all of its propulsion functions, using such a system has the potential to address many of the propellant/tank management issues that are inherit with classic VTOL/SSTO launch systems (acquiring propellant in the large LO2 and LH2 propellant tanks during all phases of flight and the typical dry weight penalty, and design complexity to meet such a vehicle requirement, demanding vehicle control requirements, and boil-off). Gelled O2/H2/Al and NTO/MMH/Al, upper stage based systems are also examined in this work and compared in terms of payload performance to a SOA O2/H2 upper stage system to provide the demanding payload orbit insertion function for typical VTOL/SSTO type launch vehicles. High-performance gelled propellant upper stage systems have the potential to provide many ground processing and system safety advantages, with improved or equal payload performance, over current SOA upper stage options.

The following discussion first provides insight into the technology status of gelled propulsion and its potential to support future SSTO applications, and then summarizes the AUGMENT-SSTO launch system operational concept,. A top-level description of the AUGMENT-SSTO launch vehicle designs considered are then given, and highlights of their key attributes (novel features) are provided, Payload performance of these systems are also discussed in detail. Additionally, this discussion also addresses the gelled propellant upper stage design assessment analysis and its corresponding payload performance results. Major design and operational attributes associated with these systems are identified throughout the paper.

II. Gelled Propellant Propulsion Technology Status

Gelled rocket propellants have been considered for many different applications.[8-26] While operational usage has not yet come to fruition, there are many technology programs that are underway to eliminate the unknowns with gelled propellants and the propulsion systems that will use them. Numerous studies have shown the potential benefits of gelled fuels and oxidizers. Technology programs to prove the combustion performance of gelled propellants have been conducted most recently by the U.S. Army Missile Command, with their industry and university partners, for tactical missile applications. The NASA Lewis Research Center and its partners have investigated O2/H2/Al and O2/RP-1/Al for NASA missions and conducted experimental programs to validate elements of the combustion and fuel technology. Gelled and metallized gelled hydrogen and RP-1 have been emphasized because hydrogen and RP-1 are typical propellants for NASA launch vehicles and upper stages. Derivatives of these propellants are therefore preferred to minimize the incremental risk for a newly introduced propulsion concept.

The benefits of gelled hydrogen and other propellants have been known for many years and experimentally proven in the past.[8-12,27-32] For gelled hydrogen there are five major benefits: safety increases, boil-off reductions, density increases with the attendant area and volume related mass reductions for related subsystems (thermal protection system, structure, insulation, etc.), slosh reductions, and Isp increases in some cases.

Safety can be significantly increased with gelled fuels. A higher viscosity reduces the spill radius of the gelled hydrogen and limits the potential damage and hazard from a fuel spill. Another important advantage is the potential for leak reduction or elimination. The leak paths from the feed systems would be minimized and the possible explosion potential would be reduced.

Boil-off reduction is another feature of gelled hydrogen. The boil-off reductions are up to a factor of 2 to 3 over ungelled liquid hydrogen.[8,11,12] This feature will assist in long term storage of hydrogen for upper stages that must sustain on-orbit storage or long coast times. Additionally, lunar flight and interplanetary missions with large hydrogen fuel loads will derive a benefit.

Significant density increases are possible with gelled hydrogen. A 10% density increase is possible with 10% added ethane or methane. These gellants are introduced into the hydrogen as frozen particles that form a gel structure in the hydrogen.[11,12]

Specific analyses of the performance gains for various missions are dependent on the vehicle and mission design.[18, 19, 33] Systems analyses performed for higher density hydrogen vehicles have shown that the reductions of the gross lift off weight (GLOW) for increased density hydrogen are very significant. In cases where another high density hydrogen, slush hydrogen was used, the density increased by 16%, the GLOW was reduced by 10.2%, or 102,000 lbm.[25,26] For airbreathing vehicles, such as the NASP the estimated reduction in GLOW for slush hydrogen was from 20 to 50%. Thus, a gelled hydrogen with a 10% density increase may deliver a significant fraction of these GLOW reductions and other subsystem mass savings.[25, 26]

The Isp of a gelled hydrogen powered vehicle may also increase over a liquid hydrogen powered vehicle, in some cases. Figure 1 shows the Isp variations for gelled hydrogen over an methane (CH_4) percentage range of 0% to 70%. This range was selected to cover the typical values of added gellant percentages investigated in past experimental work. In addition, these gellant percentages many offer attractive density increases for future vehicles. Table 1 provides the mixture ratios for the different methane loadings. Oxygen is the oxidizer, the expansion ratio is 40:1 and the chamber pressure is 2250 psia. A 94% Isp efficiency is used to compute the delivered Isp. The maximum Isp occurs at a 5% CH_4 loading and this performance level is 4 seconds higher than ungelled O_2/H_2.

For rocket and/or airbreathing propulsion, the largest volume of the vehicle is the hydrogen tank. Therefore, the volume reductions enabled by gelled hydrogen may be significant and this effect cascades into other subsystems for significant further mass and volume reductions. The subsystems that are affected are the aerodynamic thermal protection systems, cryogenic insulation, structural masses, and all of the other subsystems influenced by the hydrogen fuel tankage. A higher viscosity for the gel will also reduce the slosh modes in a propellant tank. Slosh baffle size and mass reductions are therefore possible by using gelled propellants. These masses can be very significant for a launch vehicle application.

Another option with gelled propellants is adding metal particles. Metallized gelled propellants may have modestly higher specific impulses (Isp increases of 5 to 6 lbf-s/lbm for $O_2/H_2/Al$ system, 60 wt % Al in the H_2/Al fuel) compared to nonmetallized hydrogen fuels. For proposed NASA Mars evolution and expedition missions, it has been estimated that metallized gelled $O_2/H_2/Al$ propellants can result in a 20 to 33% improvement in surface payload delivery capability.[18] More importantly for O_2/RP-1/Al and NTO/MMH/Al propellants, adding metal can deliver considerably higher propellant density, depending on the application. Hence, both the tankage mass as well as the overall propulsion system dry mass can be substantially reduced. The propellant density increases and their attendant Isp changes with the aluminum additives allow a payload increase of 14 to 35% by replacing the Space Shuttle Solid Rocket Booster with a Liquid Rocket Booster using O_2/RP-1/Al and NTO/MMH/Al, respectively.[19]

In summary, the gelled propellant combinations, with their solid technology base, and the operational attributes associated with them, make them an attractive option to consider in any future SSTO launch system where operational cost and robust operations are critical system requirements.

Many of these attributes associated with gelled propellant propulsion systems are also true for hybrid propellant propulsions. Discussion associated with these attributes and the supporting technology base associated with hybrid propulsion systems is provided in the past HYP-SSTO concept study work.[7]

III. Launch System and Vehicle Description

The AUGMENT-SSTO launch system concept is portrayed in Figure 2, while Table 2 summarizes vehicle propulsion subsystem usage by mission phase. The initial launch phase requires a main propulsion LO_2/LH_2 burn to achieve a parking orbit. The gelled propellant or hybrid auxiliary propulsion system (APS) is then used during the final orbit insertion phase of flight. Once the proper orbital velocity and inclination is achieved, the vehicle then configures itself for payload delivery or retrieval. Major orbit maneuvering burns are performed with the APS. The APS is also used to perform the deorbit burn. On reentry, aerobraking (through nose forward reentry maneuvering) is the primary deceleration mode. During the terminal landing phase of flight, the APS is fired to steer the vehicle to a gentle landing on the pad. When the terminal launch phase is initiated, the extendible communications boom is deployed. The vehicle receives Global Positioning System (GPS) position updates and highly accurate rate information. Additionally, the position beacon transmitter, laser ranger, and television camera are activated. The highly accurate landing position concept is used to guide the vehicle with minimum hover time. After landing and completion of initial safing operations, the system's health monitoring data is retrieved and critical components are inspected. This is followed by on-pad maintenance and refurbishment as required. A minimum of launch base assets, personnel and equipment, are required to support this launch system concept.

A representative AUGMENT-SSTO vehicle concept is shown in Figure 3. Table 3 highlights the design, technology, and operational features associated with this design concept. To determine dry mass of a particular AUGMENT-SSTO launch vehicle concept and its major subsystems, weight scaling relationships for many of the vehicle's major subsystems where derived from the baseline HYP-SSTO vehicle concept that was previously assessed.[7] Table 4 displays the dry weight scaling relationships, as well as their supporting assumptions and limitations. It should be noted that the HYP-SSTO based vehicle subsystem dry weight scaling relationships used in the evaluation of the AUGMENT-SSTO concept are based on "first-principle" engineering knowledge and propulsion system design experience. Though some uncertainty in these weight estimates may be present, these uncertainties are considered well within the that shown in similar preliminary SSTO launch vehicle studies done in the past. To address uncertainties pertaining to estimating the dry weight of a particular launch vehicle concept design contingency margins of 10, 20 and 30% were examined in the assessment. Unless otherwise noted, the 20% design contingency margin is considered as the nominal value in the discussion of a particular launch vehicle concept's dry weight.

The major exception to the HYP-SSTO based dry mass scaling relationships are those pertaining to the liquid and gelled O2/H2, NTO/MMH, and O2/RP-1 APSs. In determining the dry mass of these launch vehicle APSs, the following general mass-scaling equation was used:

$$\mathrm{Mdry} = \mathrm{A} + (\mathrm{B} \bullet \mathrm{Mp}), \qquad (1)$$

where A and B are scale parameter coefficients, and Mp and Mdry are the propulsion system propellant and dry mass in kilograms, respectively. Table 4 list the propulsion mass-scaling parameters for all of the APS systems examined. These parameters include all of the masses that are required to store and deliver propellants to the main engines. They include tankage, engines, feed system, thermal control, and structure. Residuals and contingency factors are not included in these relations, but are incorporated into the design analysis after the zero contingency dry and propellant system weights are determined. Also included is the weight relationships are the interface and component aerodynamic structure of the APS, and other intertank structures, as needed. It is assumed that power and other support systems are provided by the corresponding primary AUGMENT-SSTO vehicle systems. These mass scaling parameters were derived from the results of past studies and the results of propellant tank mass estimation codes. The parameter A of the scaling equations (see Equation 1 and Table 4) varies due to the different engine and propulsion system configuration layout, and subsystem masses of the differing APS options considered in the study. The B parameter is dependent upon the propellant mixture ratios, the gelled propellant metal loading and hence the propellant density. The specific mixture ratios and the metal loadings that were baselined are listed in Table 5.[19,33] Engine performance considerations are discussed in detail in Appendix A.

All of the tankage configurations considered in the study were based on the ability to package the boosters within a current launch vehicle's length and diameter constraints. Typically, the main tankage is cylindrical with ellipsoidal dome ends. The smaller tankage for the pressurization systems was spherical.

The propellant tankage for all of the pump-fed systems is designed for a 50-psia maximal operating pressure. The propellant is stored at 30 psia. All of the tankage for O2, H2 and RP-1 is composed of aluminum alloy (2219-T87). APS tanks for the NTO and MMH propellants are made of titanium (Ti-6Al-4V). The flange factor and safety factor are 1.4 and 2.0, respectively, for the propellant tanks. The safety factor is based on the tank material ultimate stress. It is assumed that the APS will have propellant ground support up until liftoff, no large allowance was made for propellant losses due to ground hold boil-off.

Each cryogenic O2/H2 propulsion system uses autogenous pressurization. The O2/RP-1/Al and NTO/MMH system used regulated pressurization. The pressurant is assumed to be helium. In the pressurant tank, the maximal operating pressure is 3722 psia. The storage pressure is 3444 psia. The flange factor and safety factor for the pressurant tanks are 1.1 and 2.0, respectively. For the autogenous systems, a small helium pressurization system is included. It can pressurize one-tenth of the total propellant tank volume. For thermal control, the cryogenic propellants (O2 and H2) use a high-performance multilayer insulation. The storable propellants only require a lower-performance multilayer insulation.

Two launch/orbit profiles were considered for the AUGMENT-SSTO vehicle performance assessment: 1. a 100 nautical mile, circular, 28.5^{O} east-west (E-W), low Earth orbit (LEO), which was launched from Cape Canaveral, FL; and, 2. a 100 nautical mile, circular, 90.0^{O} north-south (N-S), polar LEO which was launched from Vandenberg Air Force Base, CA. For both ascent trajectory profiles considered, the launch vehicle first is launched into an appropriate 50 x 100 nautical mile elliptic parking orbit using a MPS burn, see Figure 2 and Table 2. The AUGMENT-SSTO's APS is then used to place it into it's circular, 100 nautical orbit. A typical AUGMENT-SSTO reentry profile assumes a nose forward aerodynamic flight reentry profile where the vehicle is rotated to an aft-end forward position at approximately 35,000 feet. The vehicle has over a 10 second loiter capability to assist in landing. Table 6 summarizes the flight profile delta-velocity (ΔV) energy required for both E-W and polar vehicle flight profiles considered. Vehicle GLOWs assumed in the assessment, as a function MPS and orbit type, are shown in Table 7.

System ascent performance was estimated by performing POST (Program to Optimize Simulated Trajectories) analyses of boost trajectories. The POST model resulted in a "first-order" estimate of system performance. Trajectory pitch rates were optimized to place maximum weight into a 50 x 100 nm parking orbit. Launches from Cape Canaveral, FL (east) and Vandenberg Air Force Base, CA (polar) were simulated, as previously mentioned. In Figure 4, altitude and Mach number are shown for a typical launch profile. Time to achieve orbit is about 5.5 minutes. Vehicle weight and thrust histories are shown in Figure 5. Note that the rocket engines are throttled beginning about 110 seconds after launch due to a 3g constraint imposed during boost. A number of POST cases were run for different propellant combinations and different launch sites. These results were used as a basis for the vehicle sizing studies.

The propellant mass for each of the other flight profile regimes listed in Table 3 were estimated by evaluating the ideal rocket equation.[34] By knowing the initial mass (m_i) of the vehicle at each flight regime, the vehicle's final mass (m_f) can be estimated by

$$m_f = m_i / EXP(\Delta V/(g_c \bullet Isp)) . \qquad (2)$$

In the AUGMENT-SSTO analysis, the appropriate propulsion systems Isp is adjusted accordingly by:

$$Isp = \eta_{back-pressure} \bullet Isp_{vacuum} . \qquad (3)$$

to account for atmospheric back pressure variations for each flight regimes. The Isp back-pressure adjustment factor's ($\eta_{back-pressure}$) assumed in the assessment are shown in Table 8. The propellant mass used for each flight regime is then determined by:

$$Mp = m_i - m_f . \qquad (4)$$

The total propellant mass required for each AUGMENT-SSTO design concept considered by is found by summing the propellant mass need to perform each flight profile function. It should also be noted that a 1% propellant residual weight was included in determining propellant mass requirements. Subtracting the vehicle's total dry and propellant masses from it's initial GLOW defines the payload weight into orbit.

IV. Upper Stage System Description

Advanced, high-performance liquid and gelled O2/H2 and NTO/MMH propellant upper stage system options were also examined in this study. High specific impulse upper stage systems are a critical element in any SSTO launch vehicle concept because these systems can help off-set payload performance limitations, which are typical of such launch systems. These upper stage options considered were examined in a past study.[33] Upper stage dry scaling relationships and major design assumptions are summarized in Table 9.

The upper stage mass scaling parameters were derived from past study results and analyses using propellant tank mass estimation codes. Like the launch vehicle APS dry weight scaling relationships (see Equation 1), the parameter A of the scaling equations varies due to the different engine and subsystem masses of the differing propulsion system types and upper stage designs. The B parameter is dependent upon the propellant mixture ratios, the propellant metal loading and hence the propellant density. The specific mixture ratios for the upper stage propulsion system options considered, and their metal loadings are listed in Table 10. The metallized gelled O2/H2/Al upper stage mass scaling equation also used the most of the same design assumptions as that for the O2/H2/Al MPS. One major difference is that a small helium pressurant system is added to the upper stage system design. This design difference is representative of the using autogenous pressurization with the larger propellant load and larger volume of the O2/H2 MPS and APS versus the non-autogenous pressurization used in the non-cryogenic upper stage designs.

All of the tankage configurations considered in the study were based on the ability to package the upper stage within a reasonable VTOL/SSTO launch vehicle's length and diameter constraints. Most of the upper stage tankage was spherical, except for the H2 and H2/Al tanks, which were cylindrical with ellipsoidal dome ends. The pressurization systems also used spherical tankage.

The propellant tankage for the high-pressure pump-fed systems are designed for a 50-psia maximal operating pressure. The propellant is stored at 30 psia. All of the tankage for O2 and H2 are composed of aluminum alloy (2219-T87). The upper stage tanks for NTO and MMH are made of titanium (Ti-6Al-4V). The flange factor and safety factor are 1.4 and 2.0, respectively, for the propellant tanks. The safety factor is based on the tank material ultimate stress. Because the stages have propellant ground support up until liftoff, no large allowance was made for propellant losses due to ground boil-off in the analysis. Each cryogenic O2/H2 propulsion system uses autogenous pressurization. The NTO/MMH system used regulated pressurization, with helium as the pressurant. In the pressurant tank, the maximum operating pressure is 3722 psia. The storage pressure is 3444 psia. The flange factor and safety factor for the pressurant tanks are 1.1 and 2.0, respectively. For the autogenous systems, a small helium pressurization system is included. It can pressurize one-tenth of the total propellant tank volume. For thermal control, the cryogenic propellants (O2 and H2) assumes a high-performance multilayer insulation, while the storable propellants only use a lower-performance multilayer insulation. Upper stage engine performance is addressed in detail in Appendix A.

In addition, much of the assessment methodology applied to launch vehicle MPS and APS study were applied to this comparison analysis. To address design weight estimate uncertainties, dry weight design contingencies of 10, 20, and 30% were examined, with the 20% case considered as nominal, unless otherwise noted. Additionally, a 1% propellant residual mass was included and payload performance was determined by applying the ideal rocket equation, see Equation 3.

Upper stage options were considered that are capable of providing Delta-V (ΔV) values of 5000 and 22000 ft/sec. Such ΔV values are currently of interest to the military to conduct a number of space operation missions that employ SSTO type systems. These values represent requirements for a typical 'pop-up' launch option wherein the launch vehicle deploys the upper stage (subsequent to vehicle main engine cut-off (MECO)) at a suborbital velocity. The launch vehicle then makes an unpowered return to earth and lands downrange of the launch site. The upper stage would provide the additional 5000 ft/sec to inject the payload into a LEO orbit. A Geosynchronous-Earth-Orbit (GEO) mission would require a total of about 22000 ft/sec from the upper stage. The advantage of the 'pop-up' option is that the payload to orbit is significantly greater than that can be provided by current SSTO launch vehicle system options.

V. Launch System Results

Using the analysis methodology previously discussed in Section III, a number AUGMENT-SSTO concept approaches were quantified, as well as SOA, conventional, LO2/LH2 and gelled O2/H2 VTOL/SSTO launch systems (no APS) for comparison. The launch vehicle masses that are put into an E-W or polar initial parking orbit are given in Table 11. These mass estimates were determined from the POST modeling analysis effort. Applying these results with ideal rocket equation to determine propellant mass required to all the propulsive maneuvers for the other phases of the flight and the vehicle dry weight mass scaling equations the payload performance of the launch vehicle is determined. Table 12 through 17 show representative weight and performance characteristics for representative launch vehicles to perform E-W orbit missions, which are of interest to this study. Conventional LO2/LH2 and gelled O2/H2 launch systems are shown in Tables 12 and 13, respectively, while representative AUGMENT-SSTO design concepts are displayed in Tables 14 through 17. Additionally, polar orbit launch vehicle design were characterized in similar manner.

The results of the payload mass delivered to LEO for the launch vehicle configurations considered are presented in Table 18, as well as in Figures 6 and 7.

Ten different options were analyzed, and these combinations are listed in the figures. Figure 6 shows the payloads in LEO for the easterly launches. A 20% dry mass contingency for the MPS/APS combinations is the nominal case presented. The baseline case was the O2/H2 MPS with no APS and its payload delivered to LEO was 18,051 lbm, while the gelled O2/H2 MPS case (no APS) had a 17,762 lbm capability. These are the two highest payload cases of all of the options considered.

The second highest payload cases were the O2/H2 MPS and gelled O2/H2 MPS/APS combinations. Both options used a gelled O2/H2 APS. Their payload performances were 15,326 and 15,021 lbm, respectively. Though the use of the APS does reduce the payload performance by over 2,000 lbm, the use of the APS will place lower requirements on the throttling of the MPS engines, as well as the propellant acquisition of liquid or gelled cryogens for long orbital stays. The other 6 combinations all have similar payload performance, in the 12,000 lbm range. The best of these are the baseline O2/H2 MPS, with the O2/RP-1/Al APS, delivering a payload of 12,433 lbm.

Figure 7 compares the payload capabilities for the ten polar launch options. The trends seen in the easterly launch payloads are followed by the polar flights. The highest payload cases are the MPS options (no APS), with a payload of 10,607 lbm. As with the easterly launches, the O2/H2 MPS/APS and the gelled O2/H2 MPS/APS are the second highest payload capacity options.

The dry mass contingency assumptions can be very important to the success of the SSTO vehicle. The mass contingency is a percentage of the dry mass of the vehicle that is added over and above the dry mass resulting from designs analyses and estimates. The 20% contingency was considered the nominal value for this study. This assumption is reasonable based on the complexity of the preliminary design of the overall vehicle and the maturity of the technologies considered for use. Vehicles with flight hardware mass estimates are typically afforded a 1-5% mass contingency, detailed designs are given a 10% contingency, and preliminary designs, with some detailed analysis are allowed a larger 20% contingency. Other less complete designs with little or no detailed analyses would be considered acceptable with a 30 to 50% contingency.

Figure 8 and 9 show a range of contingency from 10 to 30%. In the easterly and polar launches, the contingency has a powerful effect. The all of the vehicles lose over 9,000 lbm of payload going from a 10 to a 30% contingency. This is particularly critical for the polar launches, as with many of the options, the payload mass drops to a very low value. With the polar launches, at a 30% contingency, only the 4 highest payload performance MPS/APS combinations have a positive payload mass in LEO. The vehicles using other MPS/APS technologies with 30% contingency have essentially no payload.

By using a gelled or hybrid propulsion system for major orbit maneuver burns and landing, this launch system concept has many advantages over conventional VTOL/SSTO concepts that use LO2/LH2 propulsion system(s) burns for all major phases of flight. One advantage is that vehicle insulation requirements can be relaxed, since little or no hydrogen boil-off is present after lift-off, thus reducing the tank structural mass (on-orbit cryogenic propellant storage is eliminated) for the gelled or hybrid APS options. For the hybrid APS it will consume oxygen from the same tank which feeds the main propulsion system, but will require separate turbopumps. These pumps will be much smaller than those required for the main propulsion system, and will constitute an added fallback propulsion source in the event of main engine failure. This is also true for the liquid/gelled APS options which are envisioned to an independent propulsion feed system. The reduced thrust of the vehicle's APS will still provide adequate thrust-to-weight (after jettison of the hydrogen fuel and part of the oxygen) to enable a safe abort from any altitude. An abort would only be necessary if more than one hydrogen/oxygen engine failure occurred before the critical mass of propellants had been consumed. Thus, there will be a sequence of flight envelope intervals as main propulsion system propellants are consumed, where more and more main engine subsystems (engine modules) can be shut down without compromising a safe abort. Finally, there will be a time after which a safe abort is possible using the hybrid APS alone, even with total shutdown of the main propulsion system. Of course, after the vehicle is at orbital altitude, the APS is more than adequate to provide full thrust for all subsequent operations, including deorbit and vertical landing.

Preliminary analysis has shown that even with the lower specific impulse associated with a hybrid propulsion, when compared to a that of a typical LO2/LH2 propulsion system, the vehicle's propellant mass fraction can be comparable to conventional VTOL/SSTO launch system concepts. This is also true if a higher performance gelled O2/H2 APS is considered. Additionally, by employing an APS propulsion system for major orbit maneuver and landing propulsive burns, the major technical issue of restarting large, dormant, LO2/LH2 propulsion systems is avoided, as well as relaxing the throttling demands of such a system. Even for a conventional type VTOL/SSTO launch vehicle design, using a gelled O2/H2 MPS can provide comparable payload performance to LO2/LH2, as well as address many of the demanding propellant management issues associated with such systems.

Another advantage of the AUGMENT-SSTO hybrid APS concept, is if one only uses the vehicle's hybrid propulsion system (no hydrogen onboard), the vehicle can easily function as a suborbital demonstration test bed and/or can also perform cross-country ferry flights for launch repositioning at various sites within the country. The same can also said for the AUGMENT-SSTO gelled APS concept if preloaded/packaged gelled APSs are supplied to the vehicle. This capability greatly increases basing flexibility and helps reduce system development risk and cost. Because gelled and hybrid propulsion systems are relatively simple, and inert (and relatively safe) by their nature, the AUGMENT-SSTO launch system concept has the potential to support short turnaround times between launch, be economical to develop, and reduce (or offer a competitive) overall system life-cycle cost. Support personnel should be able to freely work around the launch vehicle, while new refurbished hybrid propellant grain motor modules or preloaded /packaged gelled APSs are inserted in the vehicle.

VI. Upper Stage System Results

A series of analyses were completed to compare the upper stage options when used with the different MPS options. Tables 19 and 20, as well as Figures 10 through 13 compare the payload in LEO for all 8 options of upper stages with the MPS/APS options, with two different upper stage velocity changes being delivered: 5,000 ft/s and 22,000 ft/s. Easterly and polar orbit launches were assessed. Figures 10 and 11 are for 5,000 ft/s velocity change stages, and Figures 12 and 13 depict the stages delivering 22,000 ft/s. Within each figure, there are also two distinct upper stage masses that were considered. The stage masses were 15,326 and 18, 051 lbm for the easterly flights. With the polar flights, the upper stage masses were 7,970 lbm and 10,607 lbm. In both the easterly and polar launches, the lighter upper stage was used with the AUGMENT-SSTO (MPS/APS combination) launch vehicles, and the heavier upper stage was combined with the conventional VTOL/SSTO (MPS only options (no APS)). The payloads masses presented here were for the nominal 20% dry mass contingency cases.

Figure 10 shows the results for the easterly launches with all 8 MPS upper stages combinations. The most attractive overall combination, with the second highest delivered payload of 11,070 lbm, was the O2/H2 MPS, with no APS, and O2/H2 upper stage. Virtually the same performance is delivered by the baseline O2/H2 MPS (no APS), with the gelled O2/H2/Al upper stage (60-wt% Al). The gelled upper stage can deliver a payload of 11,127 lbm, which is higher than the O2/H2 stage, but must include the higher uncertainty of the metallized gelled H2/Al performance. The 60-wt% aluminum loading in the H2/Al will experience some degree of two-phase flow losses, and ultimately reduce the overall predicted payload performance of the stage. If these performance losses can be minimized, then certainly, the O2/H2/Al upper stage delivers a more attractive higher payload performance.

One of the most interesting results from this analysis was that the O2/H2 MPS /gelled NTO/MMH/Al upper stage option has a comparable performance to the O2/H2 MPS/APS - O2/H2 upper stage options. This may be a more complex system to employ from an operational standpoint. With the gelled NTO/MMH/Al upper stages, the launch team may have to deal with different fluids, and hence increase the operational complexity. This complexity, however, will be significantly reduced if the gelled upper stage were prepackaged, with little or no processing conducted at the launch site. Because the gelled NTO/MMH/Al stage uses storable propellants, its integration into the launch vehicle may be handled as with a solid rocket motor. Additional sensors to detect storable propellant leakage will be required, but the prepackaged stage transfers the complexity of a storable upper stage fueling and processing away from the launch site crew, and enables nearly the same payload mass performance as an all O2/H2 system.

Figure 11 illustrates the polar launch upper stage results. The overall trends and results for the polar launches follows those of the easterly flights. Again, with the conventional VTOL/SSTO launch vehicle with an O2/H2 upper stage performs the best, with the gelled O2/H2/Al stage option delivering essentially the same payload. The payloads were 6,226 lbm (with the O2/H2 stage) and 6,259 lbm (for the gelled

O2/H2/Al stage). As with the easterly flights, the baseline MPS (no APS) /gelled storable NTO/MMH/Al upper stage option provided comparable or higher payloads to LEO than the all O2/H2 MPS/APS - upper stage vehicles.

Figure 12 and 13 provide the results for the 22,000 ft/s velocity change upper stages. In most cases, the designs considered had very small or no payload performance compared to the 5,000 ft/s upper stages. In Figure 12, there were only four of the eight cases that delivered any payload on the easterly launch. All other cases delivered "negative" payloads. A negative or zero payload represents a case where the vehicle design must be reassessed. As a vehicle cannot deliver a positive payload, these results imply that the vehicle option is inappropriate for the assigned mission profile. A different staging method, perhaps with two upper stages, might allow a positive payload to be delivered, or a different higher energy propulsion option might be considered for the upper stage and/or the MPS/APS.

The Figure 12 results show that the positive payloads were delivered with only the combinations of O2/H2 MPS (with or without an APS) and O2/H2 or gelled O2/H2/Al upper stages. The MPS/APS combinations delivered between 374 and 440 lbm to the easterly orbit. The baseline MPS cases delivered 616 to 694 lbm. The gelled O2/H2/Al upper stage was in both cases able to deliver the highest payloads of these ranges. With the MPS/APS/upper stage combination, the gelled O/H2/Al upper stage could deliver 17.6% more payload than the O2/H2 upper stage, and with the MPS/upper stage alone (no APS), the gelled upper stage delivered 12.7% added payload.

In Figure 13, the polar flight results for the 22,000 ft/s upper stages are presented. In all cases, the payloads for these options were zero or negative, requiring reassessment of these vehicle options for this very high energy mission.

Figures 14 through 17, as well as Tables 19 and 20, present the influence of the dry mass contingency on the mass payload in LEO. The overall influence of the dry mass contingency was small in the 5,000 ft/s upper stage cases, as shown in Figure 14. Over the range of 10 to 30% contingency, the payload performance for the easterly launches dropped by only 300 to 400 lbm. The polar launch payload mass reduction going from a 10% to a 30% contingency, depicted in Figure 15, was in the range of 200 to 300 lbm.

With the data in Figures 16 and 17 for the 22,000 ft/s upper stages, the mass reduction for the easterly launches have a sensitivity to the contingency of 500 to 600 lbm, and for the polar flights, the payload reduction is 400 to 450 lbm. Thus the options using staging are much less sensitive to the dry mass contingency than the SSTO MPS/APS options. Additional staging studies would identify the "best" options for using upper stages for conventional VTOL/SSTO and AUGMENT-SSTO launch systems.

VII. Concluding Remarks

A preliminary design study was performed that examined the propulsion augmented, AUGMENT-SSTO launch system. Results from this study showed that this concept has improved (or at least competitive) payload performance when compared to conventional VTOL/SSTO launch vehicle designs currently under study. Simplified operational characteristics are enabled with the AUGMENT-SSTO design, and may outweigh the potential payload reductions for the MPS/APS-only cases. On the other hand, the concept has superior performance to conventional VTOL/SSTO designs for cases when the AUGMENT-SSTO vehicle designs carry a high energy upper stage.

The performance of a VTOL/SSTO vehicle for Earth-to-orbit payload delivery was analyzed. Ten options were considered for the MPS/APS combinations alone and 8 options using upper stages with the MPS/APS were reviewed. Both polar and easterly launches were assessed, and two different upper stage velocity changes were investigated. Using the O2/H2 MPS (no APS) combination (a conventional VTOL/SSTO launch vehicle design), a maximal payload mass of 18,051 lbm was achieved. The gelled O2/H2 MPS (no APS), the payload delivered was nearly the same at 17,762 lbm. The second highest performance options were those using O2/H2 MPS/APS and the gelled O2/H2 MPS/APS combinations, with payloads to LEO of over 15,000 lbm. Both easterly and polar flights have similar trends in the relative payload performance of the different options.

All of the 5,000 ft/s upper stage options were able to deliver significant easterly and polar payloads with the current MPS/APS vehicle designs. The highest payload options were the baseline O2/H2 MPS with and O2/H2/Al upper stage (60-wt% Al, with a payload of 11,127 lbm)) and the O2/H2 MPS, with no APS, and O2/H2 upper stage (with a 11,070 lbm payload). Essentially the same performance is delivered by the baseline O2/H2 MPS (no APS), with the gelled O2/H2/Al upper stage (60-wt% Al). The gelled upper stage can deliver a higher payload than the O2/H2 stage, but must include the higher uncertainty of the metallized gelled H2/Al performance. The 60% aluminum loading in the H2/Al will experience some degree of two-phase flow losses, and ultimately reduce the overall predicted payload performance of the stage. The 22,000 ft/s upper stages had 4 of 8 easterly launch options where payloads were able to reach LEO. None of the 22,000 ft/s upper stage options were able to deliver payloads to polar orbits. Using such a high energy stage will require a redesign of the launch vehicle system, with a higher gross lift-off weight, or higher energy propellants.

The sensitivity of the payload performance to the dry mass contingency was very strong with the launch vehicle system cases. The payload mass losses over a 10% to 30% contingency are 9,000 lbm for the MPS/APS options alone, whereas the payload mass loss for the upper stage cases was much less sensitive, and was a value of only several hundred pounds over the same 10% to 30% contingency. Careful effort must be made to assure the design is well defined and that the mission planner can have control and knowledge of the mass and its contingency. Payload performance will suffer greatly without this ability to know and affect the vehicle mass.

Like its counterparts, from the analysis, the AUGMENT-SSTO launch vehicle concept is also sensitive to propulsion system performance and vehicle structural (dry) weight, but it also exhibits numerous favorable design and operational features that are not typical of conventional VTOL/SSTO launch vehicle designs that use LO2/LH2 propulsion for all phases of flight. One major advantage is that vehicle insulation requirements can be relaxed, because, in many cases, little or no hydrogen is present after parking orbit velocity is achieved. Reducing the insulation mass, can lead to reduced propellant and tankage mass, and also consequently reduce the structural mass of the vehicle. Additionally, by employing independent gelled or hybrid propulsion system for major orbit maneuver and landing propulsive burns, the major technical issue of restarting large, dormant LO2/LH2 propulsion systems is avoided. Even for a conventional type VTOL/SSTO launch vehicle design, use of a gelled O2/H2 MPS has potential to provide comparable payload performance, as well as address many of the demanding propellant management issues associated with such systems: reduced boiloff, increased density, and reduced H2 slosh and reduced leakage. Another advantage of this concept is if one only uses the vehicle's APS, the vehicle can function as a suborbital demonstration test bed and/or perform cross-country ferry flights for launch repositioning at various sites within the country. Because gelled and hybrid propulsion systems are relatively simple and inert by their nature, this concept has the potential to support short turnaround times between launch, be economical to develop, and reduce (or provide a competitive) overall system life-cycle cost.

Like other VTOL/SSTO concepts, this concept also has some unique technology/development issue drivers that must be addressed, such as developing and space qualifying a gelled or hybrid propulsion system. Technology/development challenges for this concept are believed to be well within the realm of difficulty being considered for conventional VTOL/SSTO concepts. Planned work in the future on this VTOL/SSTO concept is to perform additional engineering design assessment studies. This study showed that a gelled propellant APS exhibits many of the design and operability features of that which is typical of a hybrid system, and significantly improves overall vehicle system performance.

The results from this initial feasibility study show that the AUGMENT-SSTO concept has the potential to meet future spacelift and that further study is recommended. The AUGMENT-SSTO concept would make a logical fall back design approach if the current SSTO launch system designs being pursued are unable to meet their goals.

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APPENDIX A. Metallized Gelled Propellant Engine Performance

Using a computer simulation code[42], the engine performance of the metallized gelled propellant combinations was estimated. The propellants were provided to the combustion chamber in the liquid state and are pump fed. The expansion ratio for the O2/H2 and O2/H2/Al (0-wt% Al) MPS engines was 40:1 and was selected based on the Space Transportation Main Engine design. The engine chamber pressure was 2,250 psia. The other APS designs used a 1000-psia chamber pressure and an expansion ratio of 30:1. The upper stage engines were designed with an engine chamber pressure of 1,000 psia, and an expansion ratio of 500:1. The chamber pressures and expansion ratios were selected based upon the designs of the various engines under consideration for future launch and Space Exploration Initiative vehicles.

Table A-1 contrasts the predicted performance of several propulsion systems with and without metallized gelled fuel. The increases in Isp are typically several seconds. An engine Isp efficiency was used to modify the code-predicted Isp. The Isp efficiency is the ratio of the engine performance shown in Table II and the code-predicted Isp. This reduction reflects the losses incurred due to the nozzle boundary layer, engine cycle inefficiencies and other propulsion system losses. The engine efficiencies were derived using the performance estimates from References 35 through 38 and comparisons with the vacuum Isp predicted by the engine code. In this analysis, metallized gelled propellants have the same engine efficiency as the non-metallized systems. There are additional losses that have not been included in this analysis that may potentially penalize the metallized gelled propellant cases, such as two-phase flow losses in the exhaust and the nozzle boundary layer, and nozzle erosion. Numerical modeling, propellant rheology experiments and hot-fire engine testing have been conducted to determine the potential engine efficiency of metallized gelled propellants.[14,16,17,20,35-41] Without the predicted increases in Isp, the advantages of these propellants are significantly reduced. Testing has shown that the traditional liquid fuels and gelled fuels with small loadings of metal additives perform with comparable Isp efficiencies.[17] At high metal loadings, additional technology to ensure complete metal combustion is needed, and investigations are continuing in this area.

The mixture ratios and the metal loading for these designs are given in Tables 5 and 10. The metal loading represents the fraction (by mass) of aluminum in the total mass of the fuel. The mixture ratio is defined as it is for traditional chemical propulsion: the ratio of the total oxidizer mass to the total fuel mass. In selecting the "best" metallized gelled system design, the propellant metal loading, its effects on the engine Isp and the propulsion system dry mass must be analyzed. Some of the issues that are important in determining the appropriate design for a metallized propulsion system are the propellant density, the performance and the system dry mass. In this preliminary analysis, the "best" design points were selected based on the results of past gelled propellant studies.[19,33] A more detailed analyses may reveal a better "best" design point.

Table A-1. Traditional and Metallized Gelled Engine Performance.

Vehicle and Propellant	Isp (s) (No Metal)	Isp (s) (Metal)	Isp Eff.	Mixture Ratio
MPS Options -				
O2/H2	439.2	--	0.940	6.0
O2/H2/Al	--	439.9	0.940	4.2
APS Options -				
O2/RP-1	324.5	--	0.920	2.7
O2/RP-1/Al	--	317.3	0.920	1.1
NTO/MMH	307.7	--	0.920	0.9
NTO/MMH/Al	--	318.9	0.920	2.0
O2/H2	439.2	--	0.940	6.0
O2/H2/Al	--	439.9	0.940	1.6
Upper Stage Options -				
NTO/MMH	321.2	--	0.938	2.0
NTO/MMH/Al	--	366.4	0.938	0.9
O2/H2	479.5	--	0.984	6.0
O2/H2/Al	--	485.4	0.984	1.6

Using the Al loadings considered in the engine performance calculations, the propellant density for the RP-1 can increase from 773 kg/m^3 to 1281 kg/m^3 (55 % Al loading in the fuel). For H2 fuel, the density can increase from 70 kg/m^3 to 168.6 kg/m^3 (H2 with a 60% Al loading). The density increase is computed using:

Metallized gelled propellant density =
1 / ([1 - ML - GL]/ liquid propellant density
+ ML / metal density
+ GL / gellant density) (A-1)

where: ML is the metal loading (60-wt% Al = 0.60), GL is the gellant loading (10-wt% CH4 = 0.10), with the Al metal density equal to 2768 kg/m^3, and the methane (CH4) gellant density (solid CH4) is equal to 520 kg/m^3.

In these preliminary analyses based on past studies, gellants were not used in the density calculations for MMH/Al, RP-1/Al or 60-wt% H2/Al. Gellants were only considered in the 0-wt% H2/Al (or gelled H2).

Table 1. Gelled H2/CH4 Mixture Ratios and Densities.

CH4 Loading (wt%)	Mixture Ratio	Density (kg/m^3)
0.0	6.0	70.00
5.0	4.2	73.17
10.0	4.2	76.63
15.0	4.2	80.44
20.0	4.3	84.65
25.0	4.3	89.33
30.0	4.3	94.55
35.0	4.2	100.41
40.0	4.3	107.06
45.0	4.2	114.65
50.0	4.2	123.39
55.0	4.1	133.58
60.0	4.1	145.60
65.0	4.0	160.00
70.0	4.0	177.56

Table 2. AUGMENT-SSTO Vehicle Propulsion Subsystem Usage by Mission Phase.

Mission Phase / Propulsion System	Launch	Orbit Circularization Burn(s)	Major On-Orbit Maneuvers	On-Orbit Adjustment Maneuvers	Deorbit Burn(s)	Reentry/ Landing
LO2/LH2	P*	---	---	---	---	---
Gelled or Hybrid	S, B/A**	P	P	B/A	P	P
Reaction Control	S	B/A	B/A	P	S	S

* P = Primary Function; S = Support Function (if/as required); B/A = Backup/Abort Function (if required)
** Baseline concept approach does not use the APS during the launch phase of flight

Table 3. Key Design, Technology and Operational Features Associated with the AUGMENT-SSTO Concept.

Design/Technology Features

- NASP Structures Technology (primary Structure/Tanks)
- NASP/SDI/BMDO High Heat-Flux Thermal Management/Materials Technology
- Modified RL-10 Engine System Technology
  - 26 Engines Paired Into 13 Modules - Integrated Into an Aft-Base Spike Nozzle Configuration
  - Highly Integrated Propellant Management feed System Employed
  - Demonstrated Aerospike Propulsion Technology is Considered a Backup Technology
- Conservative Gelled-Propellant Technology Extrapolation(s) Incorporated for the Gelled APS Version
- Proven Hybrid Propulsion Technology Used for Hybrid APS Version
  - 6 - 16,000 lbf Motors Located About the Aft-Base Region → Takes Advantage of Spike Nozzle Configuration
  - Demonstrated Restart/Stop Operation; Deep Throttling (20:1); Millisecond Response
  - Integrated LO2 Feed System with LO2/LH2 Propulsion Feed System
- SDI/BMDO Technology Derived High Performance Storable Reaction Control System Employed
- Uses SDI/BMDO Guidance, Navigation, Control, Power, Sensor, Communications Technology
- Supported by GPS
- Incorporates a Robust Health Management System
- Unpressurized Crew Compartment
- Modular Subsystem Designs/Interfaces
- Incorporates Modularized/Standardized Payload/Cargo Interfaces

Operational Features

- Minimal Amount of Ground Facility Assets Required
  - Simple Launch/Landing Pad
  - Mobile Launch Control and Propellant Storage/Feed Stations
- On-Site APS Refurbishment Operation(s)
- On-Site Payload Integration/Checkout Operation(s)
- Incorporates an Efficient Maintenance Support Program/Operation
- Maximum Use of Parallel Processing Operations

Table 4. AUGMENT-SSTO Launch Vehicle Subsystem Dry Weight Scaling Relationships Summary.

SUBSYSTEM	DRY WEIGHT SCALING RELATIONSHIP@	COMMENT(S)/RATIONALE
Primary Vehicle Structure	0.03173689 x GLOW*	[1], Likely good for vehicles with GLOWs ranging from 500,000 to 1,500,000 lbm.
Heat Shield/Spike Nozzle Structure	0.011553193 x GLOW	[1], Likely good for vehicles with GLOWs ranging from 500,000 to 1,500,000 lbm.
LO2/LH2 Main Propulsion System	0.009444879 x GLOW x TW**	[1], Stripped RL-10 engine type assembly with highly integrated feed system (from past P&W input). Vehicle provides many subsystem functions, Assumes Isp = 439.2 s (vac) at ε = 40:1.
Gelled O2/H2 Main Propulsion System	(0.009444879 x GLOW x TW) x 1.05	Assumes gelled main propulsion assembly will likely weigh 5 percent more than a conventional - type O2/H2 main propulsion system; 0-wt% H2/O2, or gelled H2 with CH4 gellant; Isp = 439.9 s (vac) at ε = 40:1.
Hybrid Auxiliary Propulsion System	0.20479663 x APSPW+	[1], Scaled from past AMROC input. Assumes Isp = 315.0 s (vac).
Gelled O2/H2 Auxiliary Propulsion System	700+(0.08408 x APSPW(kg))	Assumes 0-wt% O2/H2, or gelled H2 with CH4 gellant; Isp = 439.9 s (vac) at ε = 40:1. Based on past gelled propulsion analysis systems work. Striped down auxiliary propulsion system assumed (vehicle provides many subsystem functions).
NTO/MMH Auxiliary Propulsion System	840+(0.0650 x APSPW(kg))	Assumes Isp = 307.7 s (vac) at ε = 30:1. Based on past propulsion analysis systems work. Stripped down auxiliary propulsion system assumed (vehicle provides many subsystem functions).
Gelled NTO/MMH/Al Auxiliary Propulsion System	700+(0.05417 x APSPW(kg))	Assumes 40-wt% MMH/Al; Isp = 318.9 s (vac) at ε = 30:1. Based on past gelled propulsion analysis systems work. Stripped down auxiliary propulsion system assumed (vehicle provides many subsystem functions).
O2/RP-1 Auxiliary Propulsion System	700+(0.06225 x APSPW(kg))	Assumes Isp = 324.5 s (vac) at ε = 30:1. Based on past propulsion analysis systems work. Stripped down auxiliary propulsion system assumed (vehicle provides many subsystem functions).
Gelled O2/RP-1/Al Auxiliary Propulsion System	700+(0.05958 x APSPW(kg))	Assumes 55-wt% RP-1/Al; Isp = 317.3 s (vac) at ε = 30:1. Based on past gelled propulsion analysis systems work. Stripped down auxiliary propulsion system assumed (vehicle provides many subsystem functions).
Reaction Control System	0.001630805 x GLOW	[1], Likely good for vehicles with GLOWs ranging from 500,000 to 1,500,000 lbm.
Tank Servicing Equipment	Constant - 300 lbm	[1], Independent of vehicle size.
Thermal Control	0.002081759*GLOW	[1], Likely good for vehicles with GLOWs ranging from 500,000 to 1,500,000 lbm.
Avionics/Electric Power	Constant - 500 lbm	[1], Independent of vehicle size.
Crew Provisions (2 crew members)	Constant - 1600 lbm	[1], Independent of vehicle size.
Landing Struts	0.015443167 x VWIO++	[1], Likely good for vehicles with GLOWs ranging from 500,000 to 1,500,000 lbm.

@ Weights expressed in lbm unless noted
* GLOW = Vehicle Gross Liftoff Weight
** TW = Vehicle Initial Liftoff Thrust-to-Weight
\+ APSPW = Auxiliary Propulsion System Propellant Weight
\++ VWIO = Vehicle Weight In Orbit
[1] Past HYP-SSTO study work, AIAA Paper 96-2840[7]

Table 5. MPS, APS Rocket Engine Metal Loadings and Mixture Ratio Options - Pump-Fed.

PROPELLANT COMBINATION	METAL LOADING (%)	MIXTURE RATIO Gelled	MIXTURE RATIO Traditional
O2/RP-1	--	--	2.7
O2/RP-1/Al	55	1.1	--
NTO/MMH	--	--	2.0
NTO/MMH/Al	40	0.9	--
O2/H2	--	--	6.0
Gelled O2/H2	0 (gelled H2)	4.2	--
O2/H2/Al	60	1.6	--

Table 6. Flight Profile Delta-Velocity (ΔV) Budget Summary.

Flight Profile Regime	ΔV (ft/s) - 28 degree E-W Orbit	ΔV (ft/s) - 90 degree N-S Orbit
Ascent Trajectory Burn	29,422/29,423*	30,732/30,730
Orbit Circularization Burn(s)	92	92
Initial Reentry Deorbit Burn	92	92
Major Reentry Deceleration Burn (High Altitude)	155	155
Major Reentry Deceleration Burn (Low Altitude)	372	372
Landing/Hover	514	514

* LO2/LH2 MPS/Gelled O2/H2 MPS

Table 7. Launch Vehicle GLOW as a Function of Main Propulsion System and Orbit Type.

Main Propulsion System	28 degree E-W Orbit	90 degree N-S Orbit
LO2/LH2	722,452*	713,460
Gelled O2/H2	722,788	713.787

* in lbm

Table 8. Propulsion System Performance Back-Pressure Influence Adjustment Factor ($\eta_{back\text{-}pressure}$) Values as a Function of Flight Profile Regime.*

Flight Profile Regime	$\eta_{back\text{-}pressure}$
Ascent Trajectory Burn	Adjusted accordingly by POST analysis calculation
Orbit Circularization Burn(s)	1.000
Initial Reentry Deorbit Burn	1.000
Major Reentry Deceleration Burn (High Altitude)	0.889
Major Reentry Deceleration Burn (Low Altitude)	0.825
Landing/Hover	0.825

* $Isp=\eta_{back\text{-}pressure} \bullet Isp_{vacuum}$

Table 9. Upper Stage Dry Weight Scaling Relationships and Design Assumptions Summary.*

SYSTEM	DRY WEIGHT SCALING RELATIONSHIP**	DESIGN ASSUMPTIONS
O2/H2 Upper Stage	373.8+(0.1576 x USPW$^+$)	High-pressure, pump-fed system; Isp = 479.5 s (vac) at ε = 500:1.
Gelled O2/H2/Al Upper Stage	373.8+(0.1584 x USPW)	High-pressure, pump-fed system; Isp = 485.4 s (vac) at ε = 500:1.
NTO/MMH Upper Stage	440.0+(0.1358 x USPW)	High-pressure, pump-fed system; Isp = 341.2 s (vac) at ε = 500:1.
Gelled NTO/MMH/Al Upper Stage	440.0+(0.1345 x USPW)	High-pressure, pump-fed system; Isp = 366.4 s (vac) at ε = 500:1.

* Based on Past Upper Stage Study Work[33]
** Weights expressed in kg unless noted
$^+$ USPW = Upper Stage System Propellant Weight

Table 10. Upper Stage Rocket Engine Metal Loadings and Mixture Ratios - Pump-Fed.

PROPELLANT COMBINATION	METAL LOADING (%)	MIXTURE RATIO	
		Gelled	Traditional
NTO/MMH	--	--	2.0
NTO/MMH/Al	50	0.9	2.0
O2/H2	--	--	6.0
O2/H2/Al	60	1.6	--

Table 11. Launch Vehicle Mass into the Initial Parking Orbit (50 x 100 nm) as a Function of Main Propulsion System and Orbit Type.

Main Propulsion System	28 degree E-W Orbit	90 degree N-S Orbit
LO2/LH2	90,062*	81,070
Gelled O2/H2	90,399	81,397

* in lbm

Table 12. Conventional LO2/LH2 VTOL/SSTO Launch Vehicle Performance and Mass Estimate - No APS/E-W Orbit Profile.

Launch to Parking Orbit[a]		Launch/Landing	Cape Canaveral, FL
Lift-off Weight - GLOW (lbm)	722,452	Parking Orbit (nautical mile)	50 x 100 - E-W
Weight after Initial Ascent (lbm)	90,062	Final Orbit (nautical mile)	100 x100 - E-W
ΔV (ft/sec)	29,442		
Specific Impulse (s)	439.2	Ignition Thrust/Weight	1.42
Required Propellant (lbm)	632,390	Required Ignition Thrust (lbf)	1,026,400
Orbit Circularization Maneuver[b]		Dry Weight (lbm)	
ΔV (ft/sec)	92.0		
Specific Impulse (s)	439.2	Primary Vehicle Structure	22,928
Required Propellant (lbm)	585.0	Heat Shield/Spike Nozzle Structure	8,347
		LO2/LH2 Main Propulsion System	9,694
Initial Reentry Deorbit Maneuver[b]		Augmentation Propulsion System	0
ΔV (ft/sec)	92.0	Reaction Control System	1,178
Specific Impulse (s)	439.2	Tank Servicing Equipment	300
Required Propellant (lbm)	580.7	Thermal Control	1,504
		Avionics/Electric Power	500
Major Reentry Deceleration Maneuvers[b]		Crew Provisions (2 Crew Members - 450 lbm)	1,600
ΔV (ft/sec)	155.0	Landing Struts	1,390
Specific Impulse (sec)	391.0		
Required Propellant (lbm)	1,088.7	Subtotal	47,442
ΔV (ft/sec)	372.0	Dry Weight Margin (20%)	9,488
Specific Impulse (sec)	363.0		
Required Propellant (lbm)	2,753.1	Total	56,930
Landing/Hover Maneuver(s)[b]		Propellant Residuals (1%)	6,411
ΔV (ft/sec)	514.0		
Specific Impulse (sec)	363.0	Payload (lbm)	18,051
Required Propellant (lbm)	3662.5		
		Propellant Mass Fraction	0.896

a = LO2/LH2 MPS Used; b = LO2/LH2 MPS Used

Table 13. Gelled O2/H2 VTOL/SSTO Launch Vehicle Performance and Mass Estimate - No APS/E-W Orbit Profile.

Launch to Parking Orbit[a]		Launch/Landing	Cape Canaveral, FL
Lift-off Weight - GLOW (lbm)	722,788	Parking Orbit (nautical mile)	50 x 100 - E-W
Weight after Initial Ascent (lbm)	90,399	Final Orbit (nautical mile)	100 x100 - E-W
ΔV (ft/sec)	29,423		
Specific Impulse (s)	439.9	Ignition Thrust/Weight	1.42
Required Propellant (lbm)	632,389	Required Ignition Thrust (lbf)	1,026,400
Orbit Circularization Maneuver[b]		Dry Weight (lbm)	
ΔV (ft/sec)	92.0		
Specific Impulse (s)	439.2	Primary Vehicle Structure	22,939
Required Propellant (lbm)	586.0	Heat Shield/Spike Nozzle Structure	8,351
		LO2/LH2 Main Propulsion System	10,179
Initial Reentry Deorbit Maneuver[b]		Augmentation Propulsion System	0
ΔV (ft/sec)	92.0	Reaction Control System	1,179
Specific Impulse (s)	439.9	Tank Servicing Equipment	300
Required Propellant (lbm)	582.0	Thermal Control	1,505
		Avionics/Electric Power	500
Major Reentry Deceleration Maneuvers[b]		Crew Provisions (2 Crew Members - 450 lbm)	1,600
ΔV (ft/sec)	155.0	Landing Struts	1,396
Specific Impulse (sec)	391.6		
Required Propellant (lbm)	1,091.2	Subtotal	47,948
ΔV (ft/sec)	372.0	Dry Weight Margin (20%)	9,587
Specific Impulse (sec)	363.6		
Required Propellant (lbm)	2,759.0	Total	57,535
Landing/Hover Maneuver(s)[b]		Propellant Residuals (1%)	6,411
ΔV (ft/sec)	514.0		
Specific Impulse (sec)	363.6	Payload (lbm)	17,762
Required Propellant (lbm)	3670.6	Propellant Mass Fraction	0.895

a = Gelled O2/H2 MPS Used; b = Gelled O2/H2 MPS Used

Table 14. AUGMENT-SSTO Launch Vehicle Performance and Mass Estimate - Hybrid APS/E-W Orbit Profile.

Launch to Parking Orbit[a]	
Lift-off Weight - GLOW (lbm)	722,452
Weight after Initial Ascent (lbm)	90,062
ΔV (ft/sec)	29,422
Specific Impulse (s)	439.2
Required Propellant (lbm)	632,390
Orbit Circularization Maneuver[b]	
ΔV (ft/sec)	92.0
Specific Impulse (s)	315.0
Required Propellant (lbm)	814.0
Initial Reentry Deorbit Maneuver[b]	
ΔV (ft/sec)	92.0
Specific Impulse (s)	315.0
Required Propellant (lbm)	806.6
Major Reentry Deceleration Maneuvers[b]	
ΔV (ft/sec)	155.0
Specific Impulse (sec)	280.0
Required Propellant (lbm)	1,508.9
ΔV (ft/sec)	372.0
Specific Impulse (sec)	260.0
Required Propellant (lbm)	3,781.6
Landing/Hover Maneuver(s)[b]	
ΔV (ft/sec)	514.0
Specific Impulse (sec)	260.0
Required Propellant (lbm)	4,956.0

Launch/Landing	Cape Canaveral, FL
Parking Orbit (nautical mile)	50 x 100 - E-W
Final Orbit (nautical mile)	100 x100 - E-W
Ignition Thrust/Weight	1.42
Required Ignition Thrust (lbf)	1,026,400
Dry Weight (lbm)	
Primary Vehicle Structure	22,928
Heat Shield/Spike Nozzle Structure	8,347
LO2/LH2 Main Propulsion System	9,694
Augmentation Propulsion System	2,430
Reaction Control System	1,178
Tank Servicing Equipment	300
Thermal Control	1,504
Avionics/Electric Power	500
Crew Provisions (2 Crew Members - 450 lbm)	1,600
Landing Struts	1,391
Subtotal	49,873
Dry Weight Margin (20%)	9,975
Total	59,848
Propellant Residuals (1%)	6,443
Payload (lbm)	11,905
Propellant Mass Fraction	0.901

a = LO2/LH2 MPS Used; b = Hybrid APS Used

Table 15. AUGMENT-SSTO Launch Vehicle Performance and Mass Estimate - Gelled O2/H2 APS/E-W Orbit Profile.

Launch to Parking Orbit[a]	
Lift-off Weight -GLOW (lbm)	722,452
Weight after Initial Ascent (lbm)	90,062
ΔV (ft/sec)	29,422
Specific Impulse (s)	439.2
Required Propellant (lbm)	632,390
Orbit Circularization Maneuver[b]	
ΔV (ft/sec)	92.0
Specific Impulse (s)	439.9
Required Propellant (lbm)	584.0
Initial Reentry Deorbit Maneuver[b]	
ΔV (ft/sec)	92.0
Specific Impulse (s)	439.9
Required Propellant (lbm)	579.8
Major Reentry Deceleration Maneuvers[b]	
ΔV (ft/sec)	155.0
Specific Impulse (sec)	391.0
Required Propellant (lbm)	1,088.7
ΔV (ft/sec)	372.0
Specific Impulse (sec)	363.0
Required Propellant (lbm)	2,753.1
Landing/Hover Maneuver(s)[b]	
ΔV (ft/sec)	514.0
Specific Impulse (sec)	363.0
Required Propellant (lbm)	3,662.6

Launch/Landing	Cape Canaveral, FL
Parking Orbit (nautical mile)	50 x 100 - E-W
Final Orbit (nautical mile)	100 x100 - E-W
Ignition Thrust/Weight	1.42
Required Ignition Thrust (lbf)	1,026,400
Dry Weight (lbm)	
Primary Vehicle Structure	22,928
Heat Shield/Spike Nozzle Structure	8,347
LO2/LH2 Main Propulsion System	9,694
Augmentation Propulsion System	2,272
Reaction Control System	1,178
Tank Servicing Equipment	300
Thermal Control	1,504
Avionics/Electric Power	500
Crew Provisions (2 Crew Members - 450 lbm)	1,600
Landing Struts	1,391
Subtotal	49,714
Dry Weight Margin (20%)	9,943
Total	59,657
Propellant Residuals (1%)	6,411
Payload (lbm)	15,326
Propellant Mass Fraction	0.896

a = LO2/LH2 MPS Used; b = Gelled O2/H2 APS Used

Table 16. AUGMENT-SSTO Launch Vehicle Performance and Mass Estimate - Gelled NTO/MMH/Al APS/E-W Orbit Profile.

Launch to Parking Orbit[a]		Launch/Landing	Cape Canaveral, FL
Lift-off Weight - GLOW (lbm)	722,452	Parking Orbit (nautical mile)	50 x 100 - E-W
Weight after Initial Ascent (lbm)	90,062	Final Orbit (nautical mile)	100 x100 - E-W
ΔV (ft/sec)	29,422		
Specific Impulse (s)	439.2	Ignition Thrust/Weight	1.42
Required Propellant (lbm)	632,390	Required Ignition Thrust (lbf)	1,026,400
Orbit Circularization Maneuver[b]		Dry Weight (lbm)	
ΔV (ft/sec)	92.0		
Specific Impulse (s)	307.7	Primary Vehicle Structure	22,928
Required Propellant (lbm)	833.0	Heat Shield/Spike Nozzle Structure	8,347
		LO2/LH2 Main Propulsion System	9,694
Initial Reentry Deorbit Maneuver[b]		Augmentation Propulsion System	2,200
ΔV (ft/sec)	92.0	Reaction Control System	1,178
Specific Impulse (s)	307.7	Tank Servicing Equipment	300
Required Propellant (lbm)	825.5	Thermal Control	1,504
		Avionics/Electric Power	500
Major Reentry Deceleration Maneuvers[b]		Crew Provisions (2 Crew Members - 450 lbm)	1,600
ΔV (ft/sec)	155.0	Landing Struts	1,391
Specific Impulse (sec)	273.5		
Required Propellant (lbm)	1,543.7	Subtotal	49,643
ΔV (ft/sec)	372.0	Dry Weight Margin (20%)	9,929
Specific Impulse (sec)	253.9		
Required Propellant (lbm)	3,867.2	Total	59,572
Landing/Hover Maneuver(s)[b]		Propellant Residuals (1%)	6,445
ΔV (ft/sec)	514.0		
Specific Impulse (sec)	253.9	Payload (lbm)	11,914
Required Propellant (lbm)	5,061.7	Propellant Mass Fraction	0.901

a = LO2/LH2 MPS Used; b = Gelled NTO/MMH APS Used

Table 17. AUGMENT-SSTO Launch Vehicle Performance and Mass Estimate - Gelled O2/RP-1/Al APS/E-W Orbit Profile.

Launch to Parking Orbit[a]		Launch/Landing	Cape Canaveral, FL
Lift-off Weight - GLOW (lbm)	722,452	Parking Orbit (nautical mile)	50 x 100 - E-W
Weight after Initial Ascent (lbm)	90,062	Final Orbit (nautical mile)	100 x100 - E-W
ΔV (ft/sec)	29,422		
Specific Impulse (s)	439.2	Ignition Thrust/Weight	1.42
Required Propellant (lbm)	632,390	Required Ignition Thrust (lbf)	1,026,400
Orbit Circularization Maneuver[b]		Dry Weight (lbm)	
ΔV (ft/sec)	92.0		
Specific Impulse (s)	324.5	Primary Vehicle Structure	22,928
Required Propellant (lbm)	790.0	Heat Shield/Spike Nozzle Structure	8,347
		LO2/LH2 Main Propulsion System	9,694
Initial Reentry Deorbit Maneuver[b]		Augmentation Propulsion System	2,262
ΔV (ft/sec)	92.0	Reaction Control System	1,178
Specific Impulse (s)	324.5	Tank Servicing Equipment	300
Required Propellant (lbm)	783.3	Thermal Control	1,504
		Avionics/Electric Power	500
Major Reentry Deceleration Maneuvers[b]		Crew Provisions (2 Crew Members - 450 lbm)	1,600
ΔV (ft/sec)	155.0	Landing Struts	1,391
Specific Impulse (sec)	288.4		
Required Propellant (lbm)	1,466.1	Subtotal	49,704
ΔV (ft/sec)	372.0	Dry Weight Margin (20%)	9,941
Specific Impulse (sec)	267.8		
Required Propellant (lbm)	3,677.6	Total	59,645
Landing/Hover Maneuver(s)[b]		Propellant Residuals (1%)	6,439
ΔV (ft/sec)	514.0		
Specific Impulse (sec)	267.8	Payload (lbm)	12,433
Required Propellant (lbm)	4,827.1	Propellant Mass Fraction	0.900

a = LO2/LH2 MPS Used; b = Gelled O2/RP-1 APS Used

Table 18. Launch Vehicle Payload Performance Results Summary.

System Type	Percent Contingency / LEO Orbit Type	10	20	30
Baseline O2/H2 MPS*/ No APS**	28 degree E-W	22,795+	18,051	13,307
	Polar N-S	15,295	10,607	5,919
Gelled O2/H2 MPS/ No APS	28 degree E-W	22,557	17,762	12,967
	Polar N-S	15,047	10,308	5,570
O2/H2 MPS/ Hybrid APS	28 degree E-W	16,893	11,905	6,918
	Polar N-S	9,982	5,075	168
O2/H2 MPS/ Gelled O2/H2 APS	28 degree E-W	20,298	15,326	10,355
	Polar N-S	12,878	7,970	3,062
Gelled O2/H2 MPS/ Hybrid APS	28 degree E-W	16,618	11,580	6,541
	Polar N-S	9,700	4,742	NPC++
Gelled O2/H2 MPS/ Gelled O2/H2 APS	28 degree E-W	20,043	15,021	9,998
	Polar N-S	12,614	7,656	2,697
Baseline O2/H2 MPS/ Gelled NTO/MMH/Al APS	28 degree E-W	16,879+	11,914	6,950
	Polar N-S	9,800	4,898	NPC
Gelled O2/H2 MPS/ Gelled NTO/MMH/Al APS	28 degree E-W	17,314	12,353	7,392
	Polar N-S	10,192	5,293	394
Baseline O2/H2 MPS/ O2/RP-1 APS	28 degree E-W	17,404	12,433	7,463
	Polar N-S	10,273	5,365	458
Gelled O2/H2 MPS/ O2/RP-1 APS	28 degree E-W	17,173	12,205	7,236
	Polar N-S	10,065	5,159	254

* Main Propulsion System
** Augmentation Propulsion System
+ Payload weight into orbit (lbm)
++ NPC = No Payload Capability

Table 19. Conventional LO2/LH2 Launch Vehicle Payload Performance with Upper Stage Insertion - Results Summary.

System Type	Percent Contingency/ Upper Stage ΔV (ft/s) / LEO Orbit Type/Initial Stage Weight (lbm)[+]	10/ 5,000	20/ 5,000	30/ 5,000	10/ 22,000	20/ 22,000	30/ 22,000
Baseline LO2/LH2 MPS*-O2/H2 Upper Stage[a]	28 degree E-W/ 18,051	11,231[++]	11,070	10,909	915	616	318
	Polar N-S/10,607	6,226	6,097	5,968	164	NPO	NPO
Baseline LO2/LH2 MPS-Gelled O2/H2/Al Upper Stage[a]	28 degree E-W/ 18,051	11,287	11,127	10,966	993	694	396
	Polar N-S/10,607	6,259	6,130	6,002	209	NPO	-209
Baseline LO2/LH2 MPS-NTO/MMH Upper Stage[b]	28 degree E-W/ 18,051	9,326	9,139	8,952	NPO[c]	NPO	NPO
	Polar N-S/10,607	5,040	4,890	4,740	NPO	NPO	NPO
Baseline LO2/LH2 MPS-Gelled NTO/MMH/Al Upper Stage[b]	28 degree E-W/ 18,051	9,758	9,577	9,396	NPO	NPO	NPO
	Polar N-S/10,607	5,294	5,148	5,001	NPO	NPO	NPO

* Main Propulsion System
[+] Includes Upper Stage System plus Payload
[++] Payload weight into orbit (lbm)
[a] Spherical O2 Tank, Cylindrical H2 Tank
[b] Spherical Tanks
[c] NPO = No Payload into Orbit

Table 20. AUGMENT-SSTO Launch Vehicle Payload Performance with Upper Stage Insertion - Results Summary.

System Type	Percent Contingency/ Upper Stage ΔV (ft/s) / LEO Orbit Type/Initial Stage Weight (lbm)[+]	10/ 5,000	20/ 5,000	30/ 5,000	10/ 22,000	20/ 22,000	30/ 22,000
LO2/LH2 MPS*/Gelled O2/H2 APS**-O2/H2 Upper Stage[a]	28 degree E-W/ 15,326	9,399[++]	9,250	9,100	640	374	108
	Polar N-S/7,970	4,452	4,335	4,218	NPO[c]	NPO	NPO
LO2/LH2 MPS/ Gelled O2/H2 APS- Gelled O2/H2/Al Upper Stage[a]	28 degree E-W/ 15,326	9,447	9,298	9,148	706	440	174
	Polar N-S/7,970	4,477	4,360	4,243	NPO	NPO	NPO
LO2/LH2 MPS/Gelled O2/H2 APS-NTO/MMH Upper Stage[b]	28 degree E-W/ 15,326	7,757	7,584	7,410	NPO	NPO	NPO
	Polar N-S/7,970	3,521	3,384	3,248	NPO	NPO	NPO
LO2/LH2 MPS/ Gelled O2/H2 APS- Gelled NTO/MMH/Al Upper Stage[b]	28 degree E-W/ 15,326	8,124	7,956	7,788	NPO	NPO	NPO
	Polar N-S/7,970	3,712	3,578	3,444	NPO	NPO	NPO

* Main Propulsion System
** Augmentation Propulsion System
[+] Includes Upper Stage System plus Payload
[++] Payload weight into orbit (lbm)
[a] Spherical O2 Tank, Cylindrical H2 Tank
[b] Spherical Tanks
[c] NPO = No Payload into Orbit

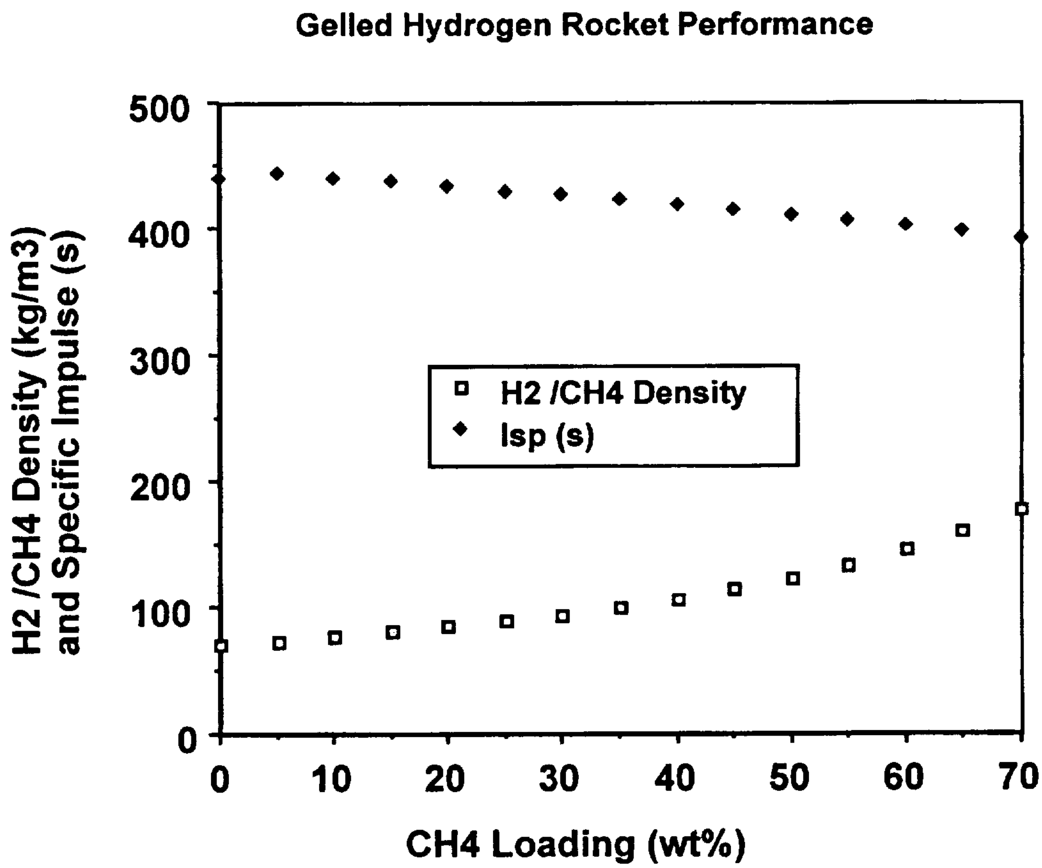

Figure 1. Gelled Hydrogen Rocket Engine Specific Impulse (Oxygen as oxidizer, 2250 psia chamber pressure, expansion ratio = 40:1).

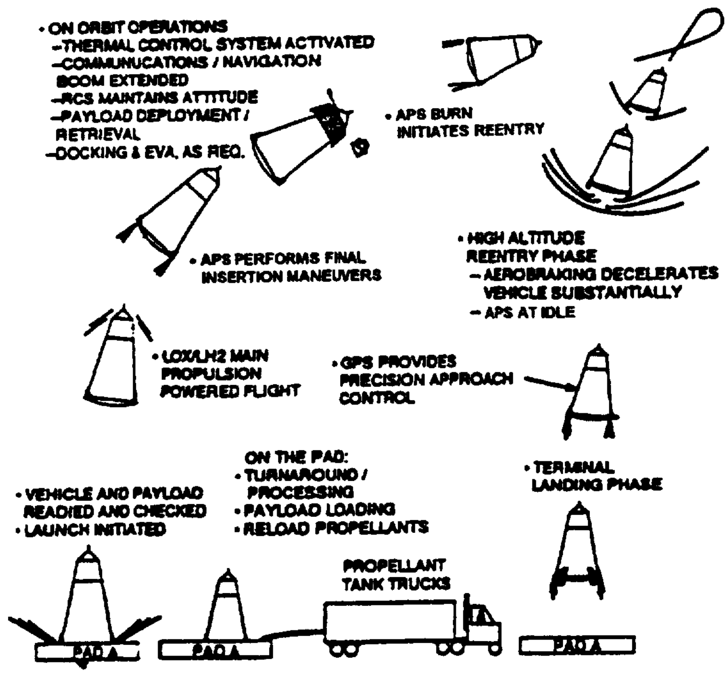

Figure 2. AUGMENT-SSTO System Concept Architecture.

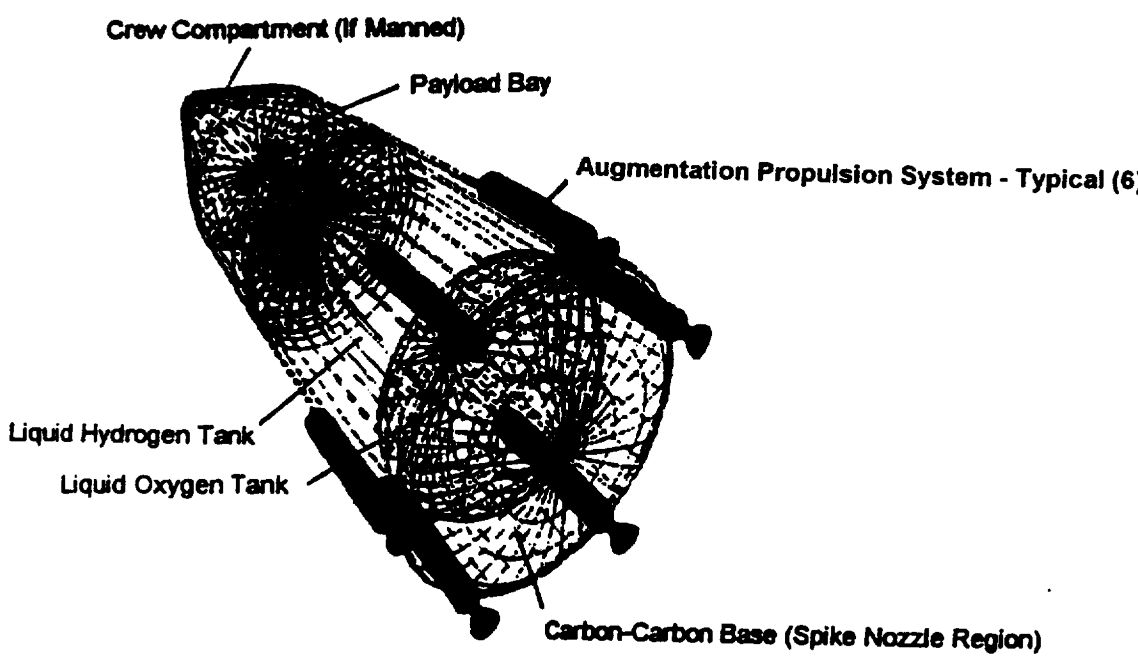

Figure 3. Representative AUGMENT-SSTO Launch Vehicle Concept (not to scale).

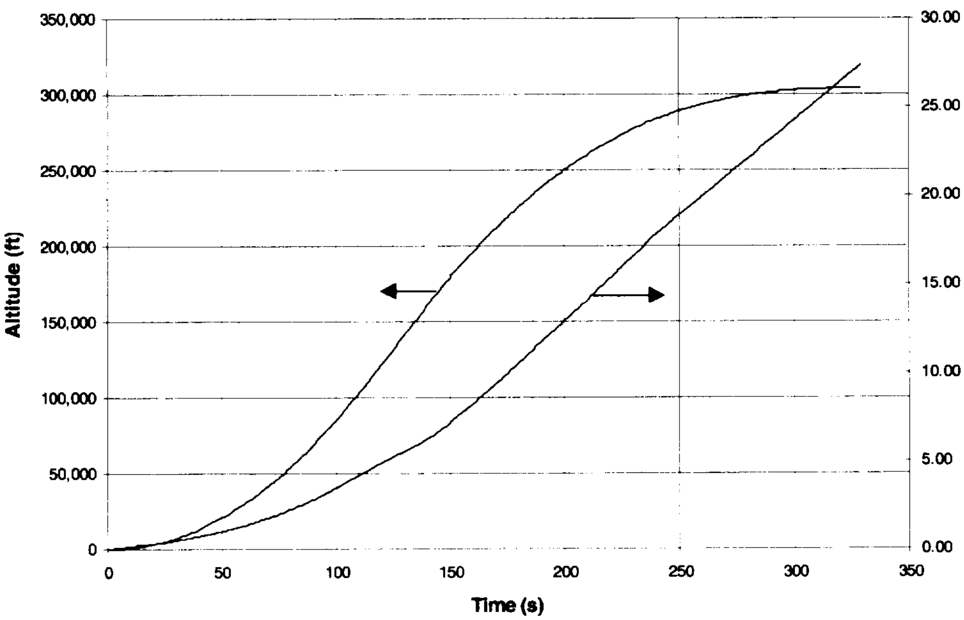

Figure 4. Typical AUGMENT-SSTO E-W Orbit Ascent Flight Parameters as a Function of Time - Mach Number and Altitude
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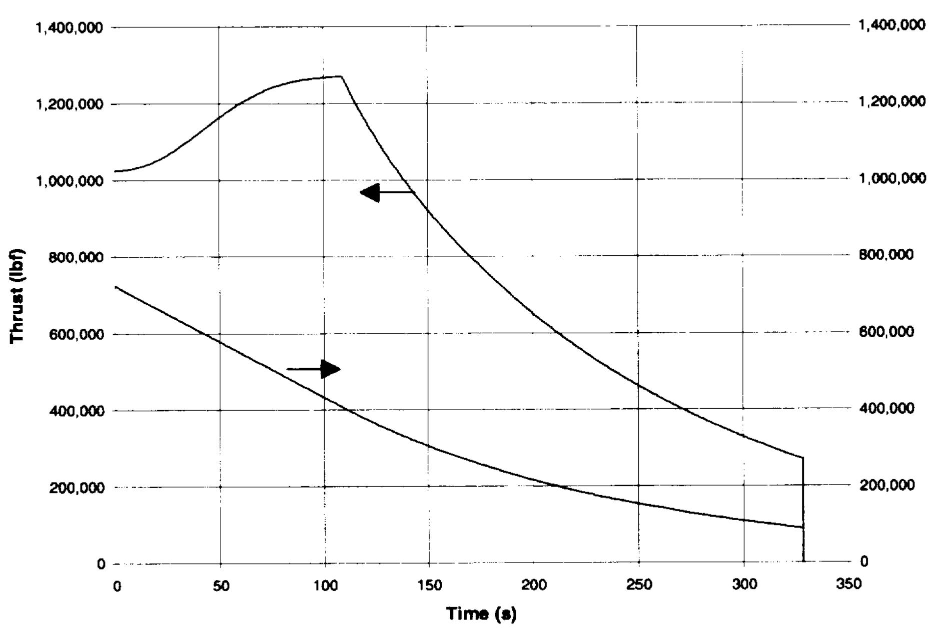

Figure 5. Typical AUGMENT-SSTO E-W Orbit Ascent Flight Parameters as a Function of Time - Thrust and Weight

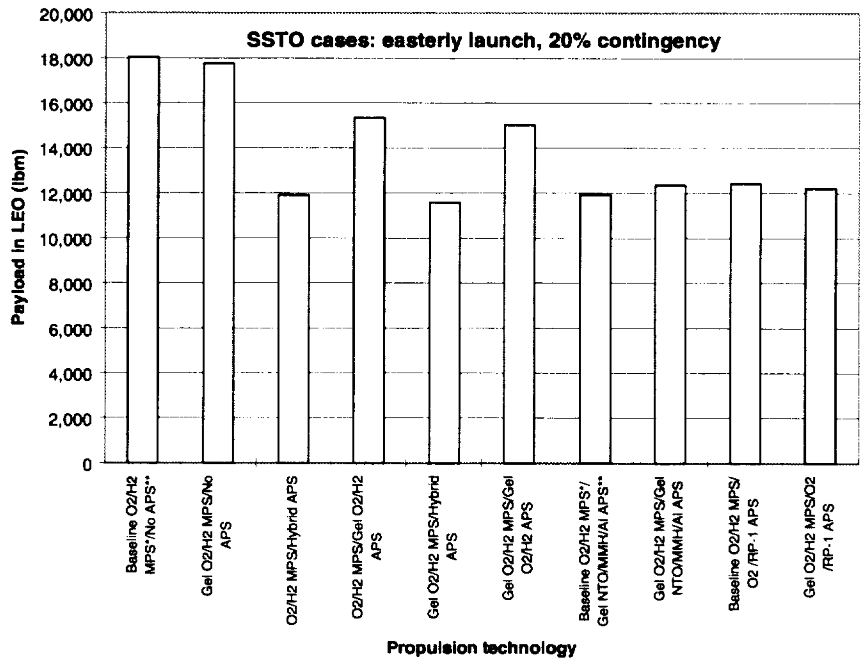

Figure 6. Payload Mass in LEO for Various VTOL/SSTO Launch Vehicle Propulsion System Combination Options - E-W Orbit Profile /20% Dry Weight Contingency.

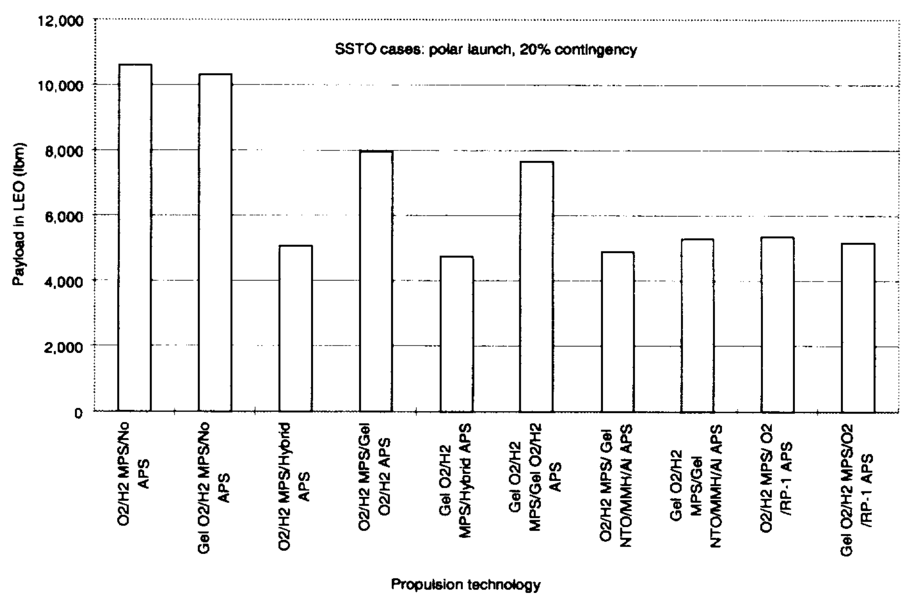

Figure 7. Payload Mass in LEO for Various VTOL/SSTO Launch Vehicle Propulsion System Combination Options - Polar Orbit Profile /20% Dry Weight Contingency.

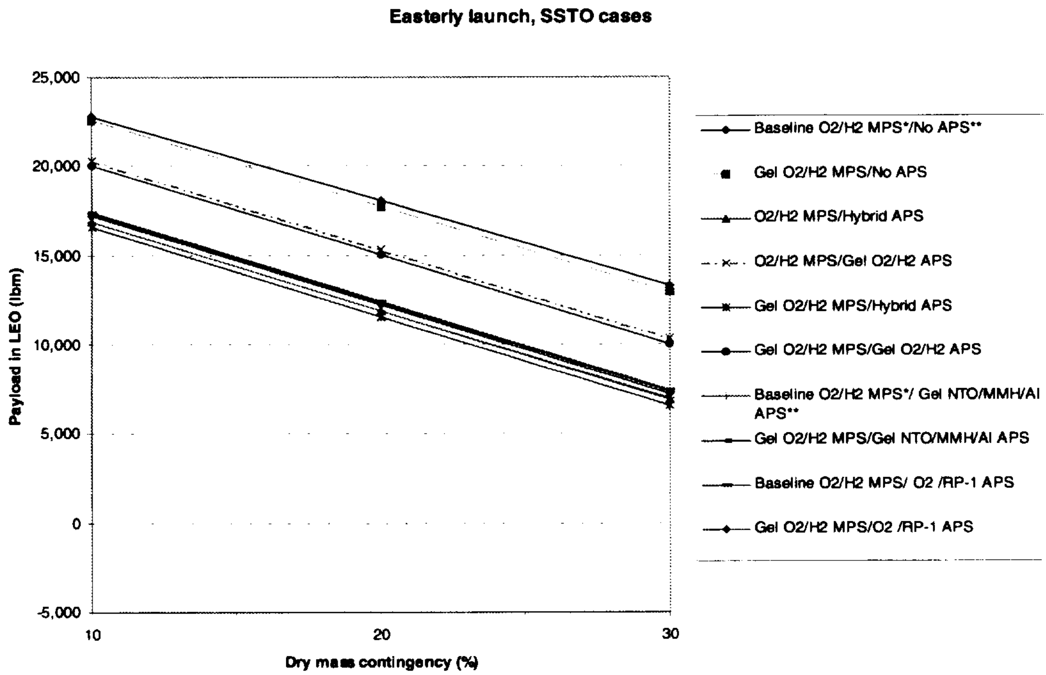

Figure 8. Effect of Dry Mass Contingency on Payload Mass in LEO - E-W Orbit Profile.

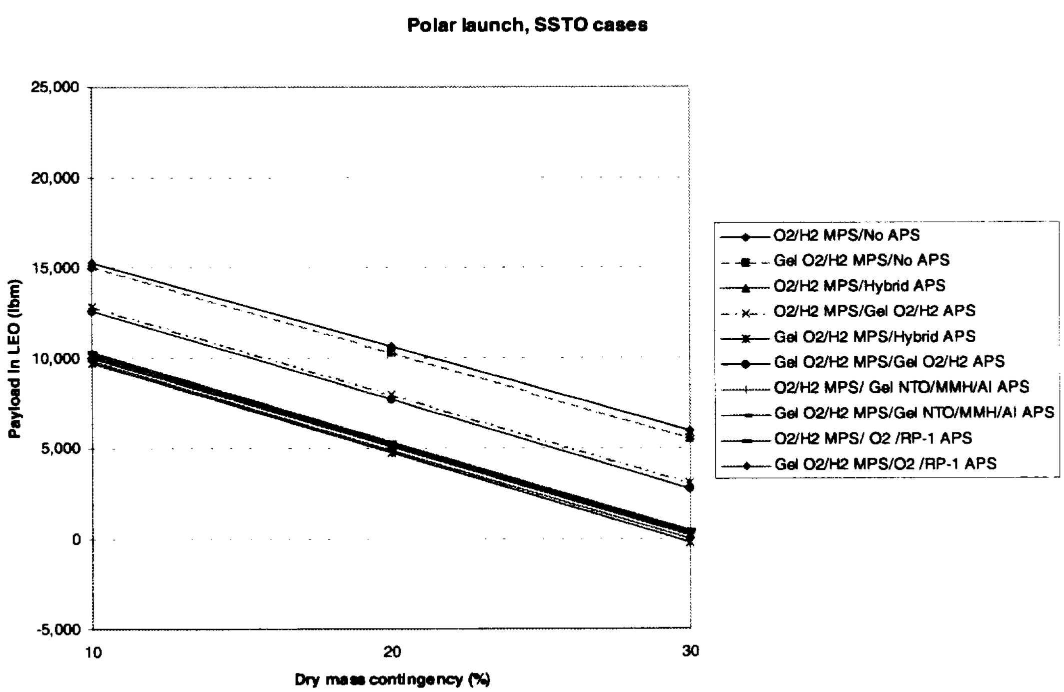

Figure 9. Effect of Dry Mass Contingency on Payload Mass in LEO - Polar Orbit Profile.

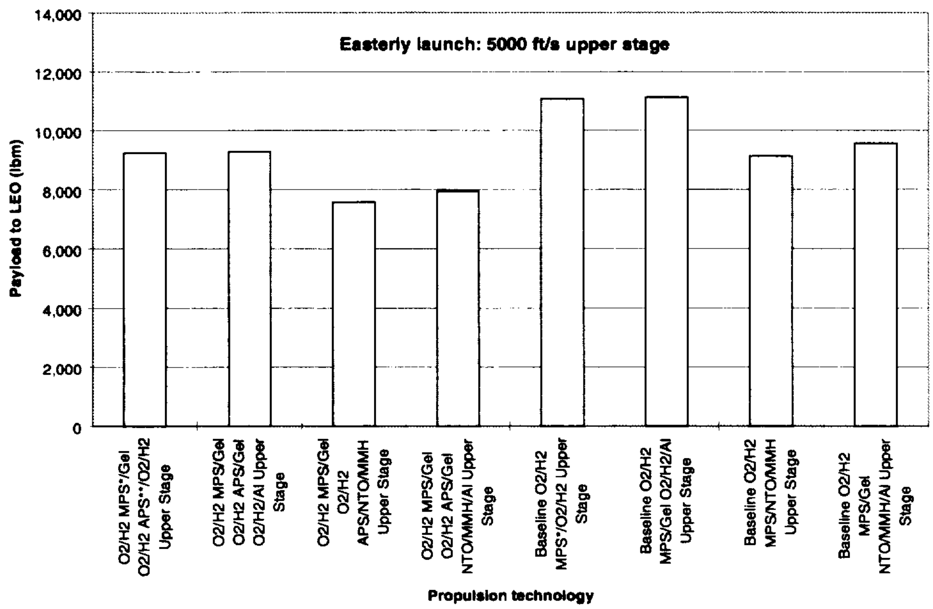

Figure 10. Payload Mass in LEO for Various VTOL/SSTO Launch Vehicle /Upper Stage Propulsion System Combination Options - 5,000 ft/s Capability /E-W Orbit Profile.

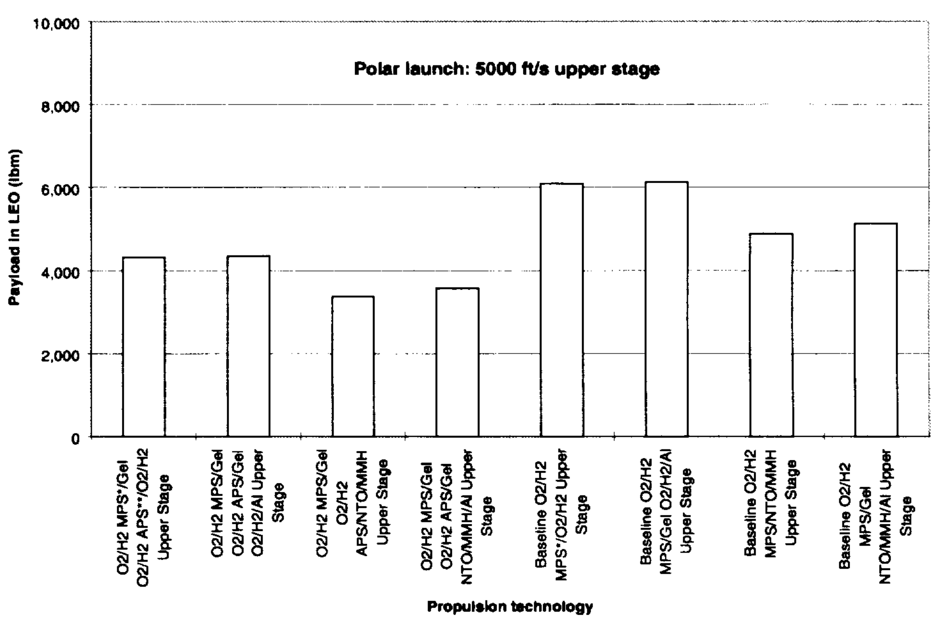

Figure 11. Payload Mass in LEO for Various VTOL/SSTO Launch Vehicle /Upper Stage Propulsion System Combination Options - 5,000 ft/s Capability /Polar Orbit Profile.

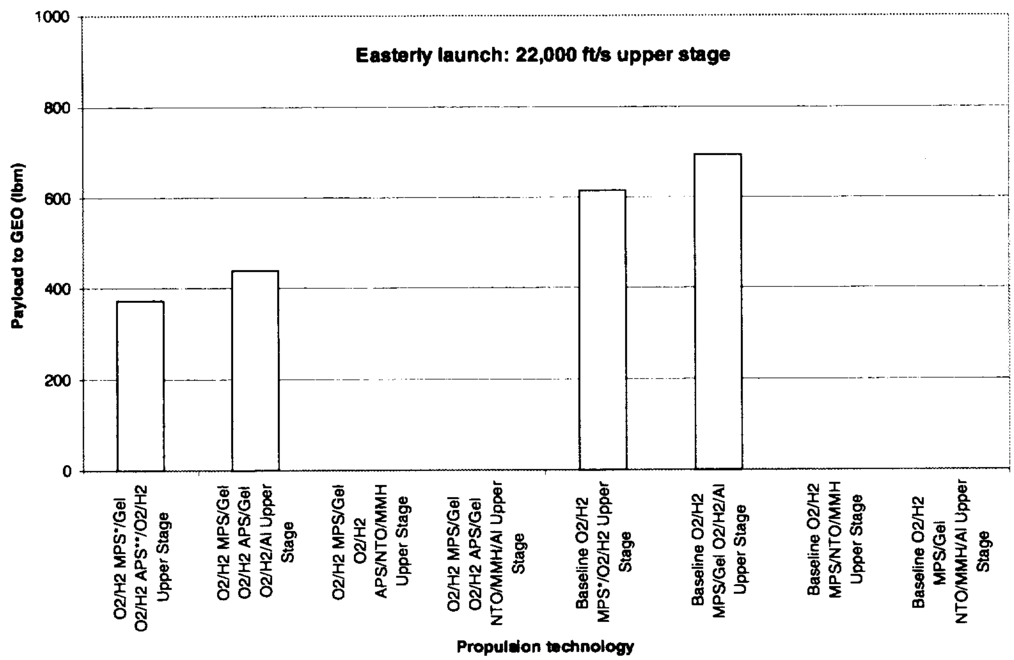

Figure 12. Payload Mass in GEO for Various VTOL/SSTO Launch Vehicle /Upper Stage Propulsion System Combination Options - 22,000 ft/s Capability /E-W Orbit Profile.

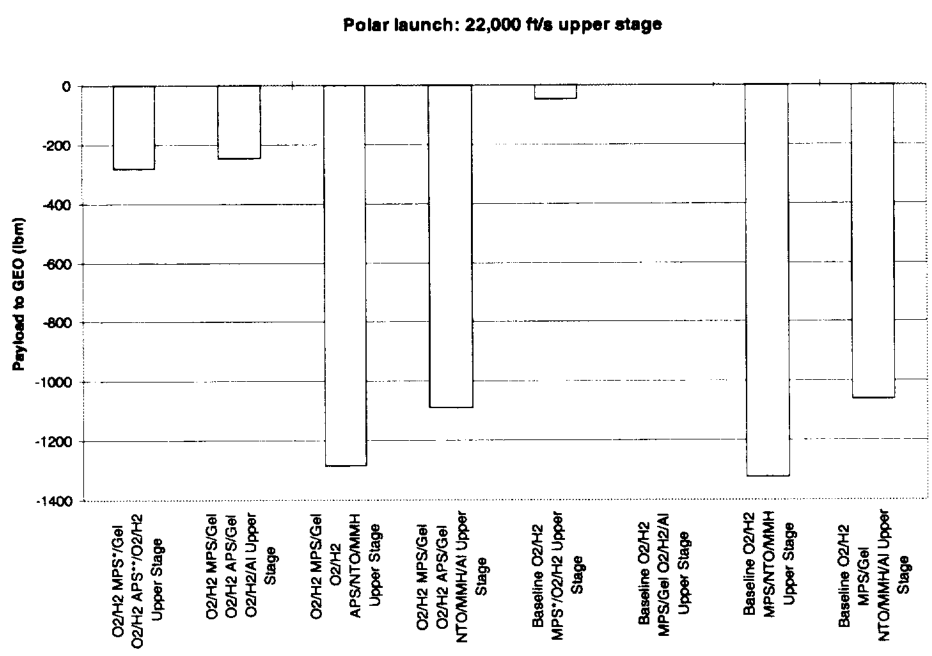

Figure 13. Payload Mass in GEO for Various VTOL/SSTO Launch Vehicle /Upper Stage Propulsion System Combination Options - 22,000 ft/s Capability /Polar Orbit Profile.

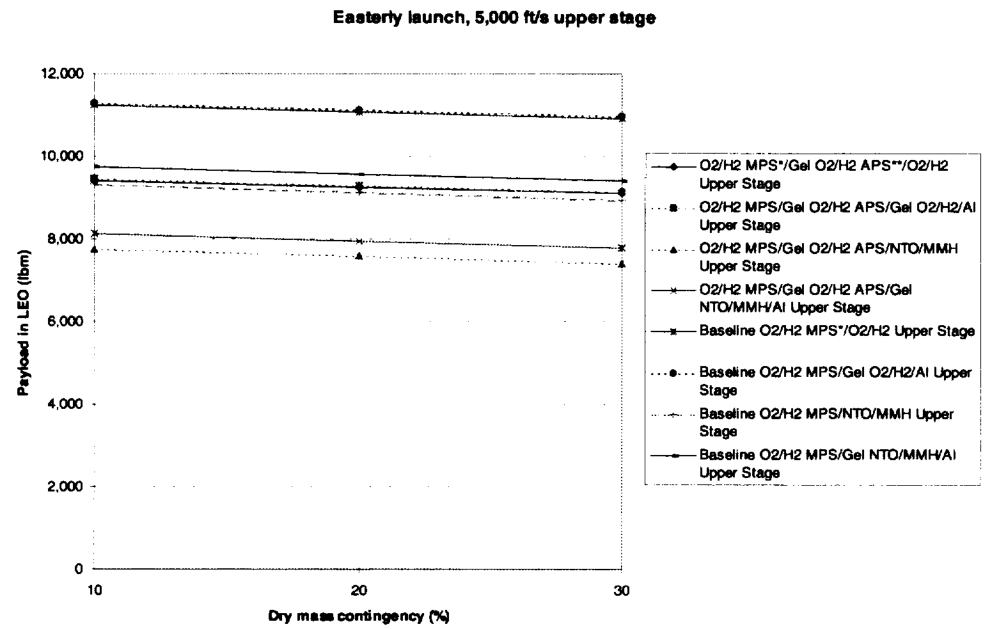

Figure 14. Effect of Dry Mass Contingency on Payload Mass in LEO - 5,000 ft/s Upper Stage /E-W Orbit Profile.

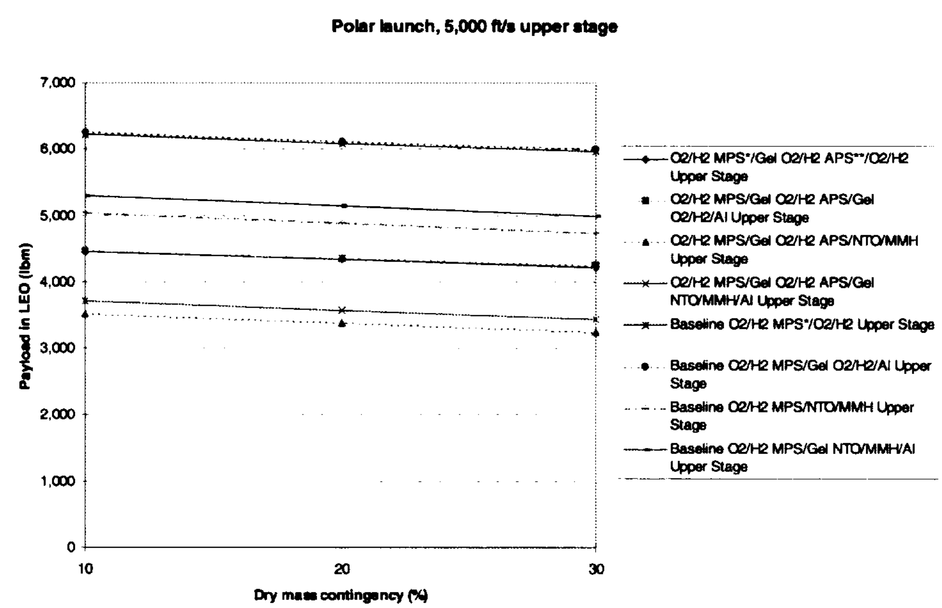

Figure 15. Effect of Dry Mass Contingency on Payload Mass in LEO - 5,000 ft/s Upper Stage /Polar Orbit Profile.

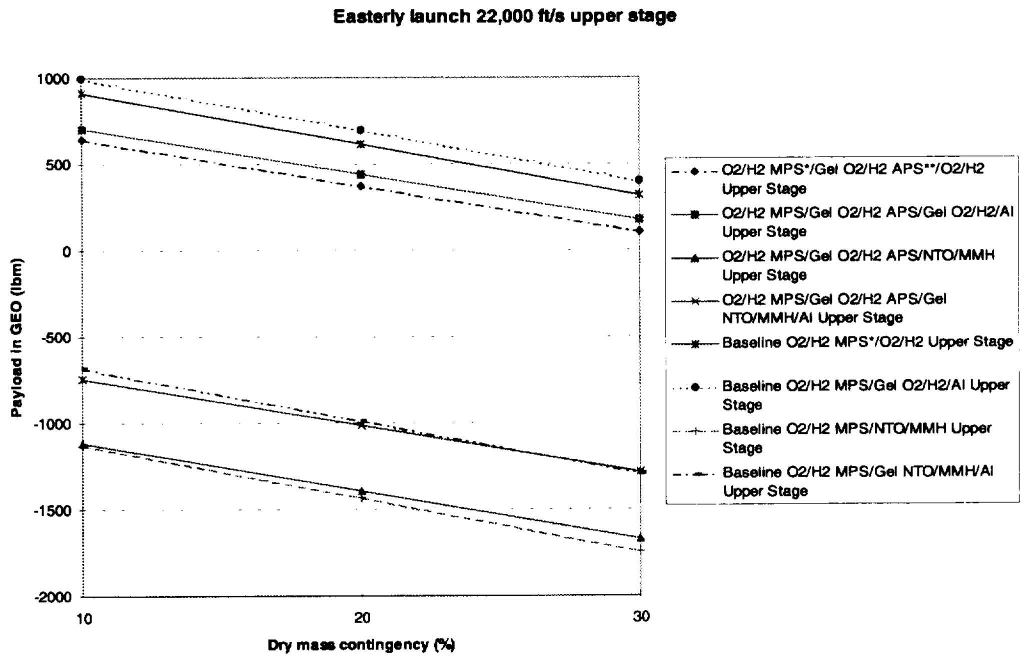

Figure 16. Effect of Dry Mass Contingency on Payload Mass in GEO - 22,000 ft/s Upper Stage /E-W Orbit Profile.

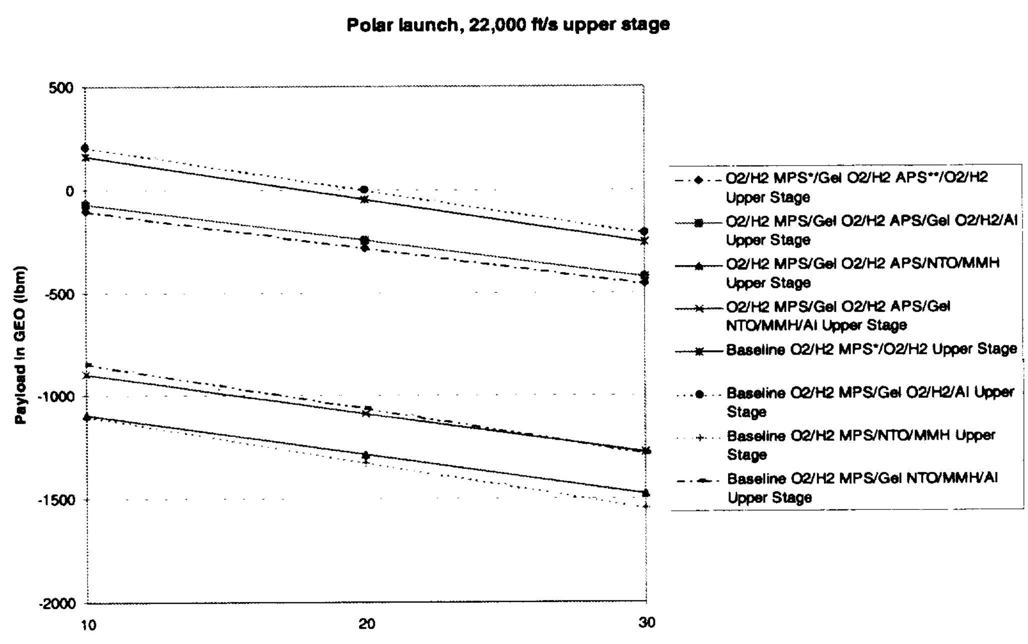

Figure 17. Effect of Dry Mass Contingency on Payload Mass in GEO - 22,000 ft/s Upper Stage /Polar Orbit Profile.

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13. ABSTRACT ***(Maximum 200 words)***

A novel, reusable, Vertical-Takeoff-and-Vertical-Takeoff-and-Landing, Single-Stage-to-Orbit (VTOL/SSTO) launch system concept, named AUGMENT-SSTO, is presented in this paper to help quantify the advantages of employing gelled and hybrid propellant propulsion system options for such applications. The launch vehicle system concept considered uses a highly coupled, main high performance liquid oxygen/liquid hydrogen (LO2/LH2) propulsion system, that is used only for launch, while a gelled or hybrid propellant propulsion system auxiliary propulsion system is used during final orbit insertion, major orbit maneuvering, and landing propulsive burn phases of flight. Using a gelled or hybrid propellant propulsion system for major orbit maneuver burns and landing has many advantages over conventional VTOL/SSTO concepts that use LO2/LH2 propulsion system(s) burns for all phases of flight. The applicability of three gelled propellant systems, O2/H2/Al, O2/RP-1/Al, and NTO/MMH/Al, and a state-of-the-art (SOA) hybrid propulsion system are examined in this study. Additionally, this paper addresses the applicability of a high performance gelled O2/H2 propulsion system to perform the primary, as well as the auxiliary propulsion system functions of the vehicle.

14. SUBJECT TERMS

Gel propellants; Launch vehicles; Upper stages; Systems analysis; Hybrid rockets

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