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Atomic Hydrogen as a Launch Vehicle Propellant

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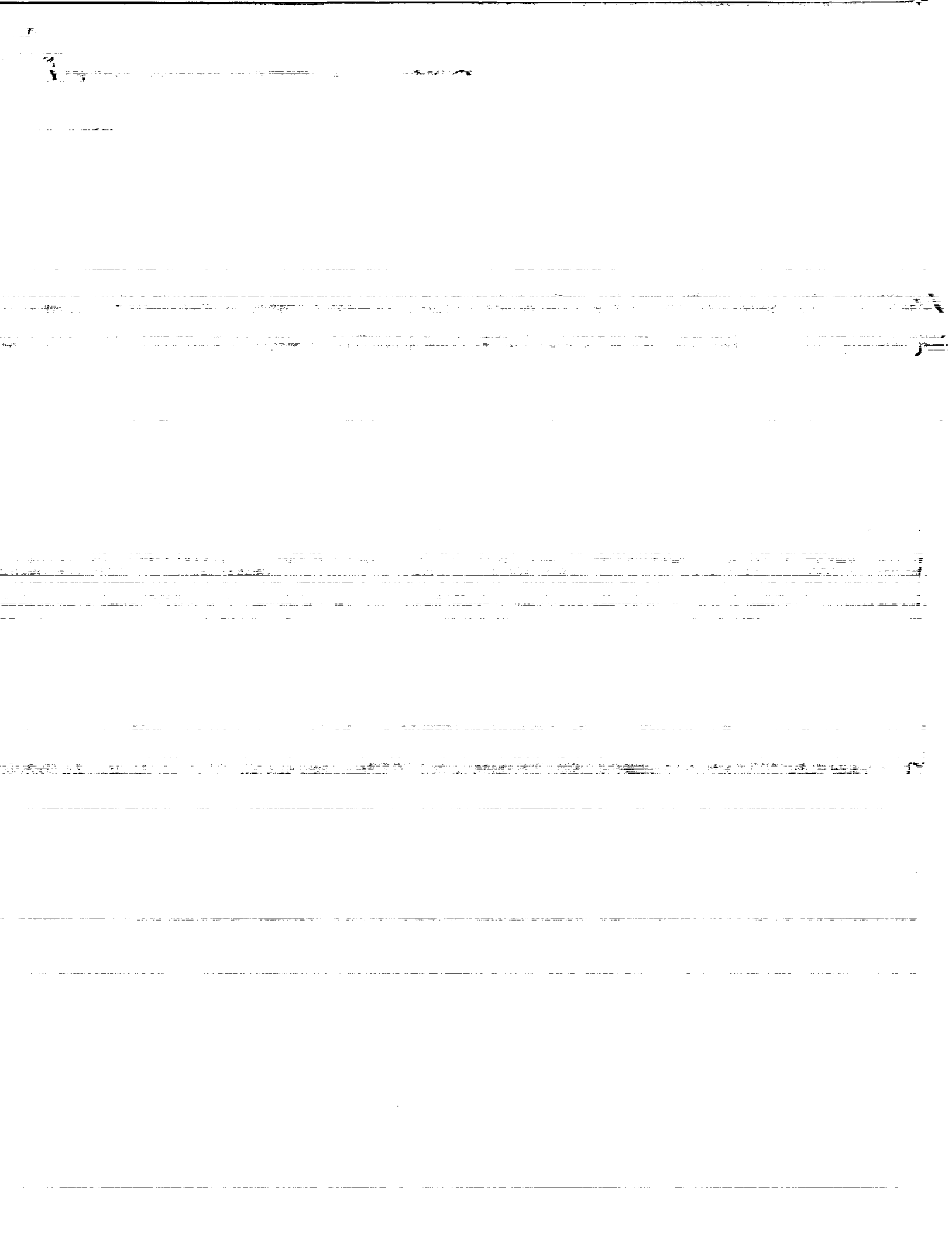
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ATOMIC HYDROGEN AS A LAUNCH VEHICLE PROPELLANT

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Abstract

An analysis of several atomic hydrogen launch vehicles was conducted. A discussion of the facilities and the technologies that would be needed for these vehicles is also presented. The Gross Liftoff Weights (GLOW) for two systems were estimated; their specific impulses (I_{sp}) were 750 and 1500 $lb_f\text{-s}/lb_m$. The atomic hydrogen launch vehicles were also compared to the currently planned Advanced Launch System design concepts. Very significant GLOW reductions of 52 to 85 percent are possible over the Advanced Launch System designs. Applying atomic hydrogen propellants to upper stages was also considered. Very high I_{sp} (greater than 750 $lb_f\text{-s}/lb_m$) is needed to enable a mass savings over advanced oxygen/hydrogen propulsion.

Associated with the potential benefits of high- I_{sp} atomic hydrogen are several challenging problems. Very high magnetic fields are required to maintain the atomic hydrogen in a solid hydrogen matrix. The magnetic field strength has been estimated to be 30 kilogauss (3 Tesla). Also the storage temperature of the propellant is 4 K. This very low temperature will require a large refrigeration facility for the launch vehicle. The design considerations for a very high recombination rate for the propellant are also discussed. A recombination rate of 210 cm/s is predicted for atomic hydrogen. This high recombination rate can produce very high acceleration for the launch vehicle. Unique insulation or segmentation to "inhibit" the propellant may be needed to reduce its recombination rate.

Nomenclature

AFAL	Air Force Astronautics Laboratory
ALS	Advanced Launch System
BECO	Booster Engine Cut Off
GLOW	Gross Liftoff Weight
HEDM	High-Energy Density Materials
IUS	Inertial Upper Stage
I_{sp}	Specific Impulse ($lb_f\text{-s}/lb_m$)
JPL	Jet Propulsion Laboratory
LEO	Low Earth Orbit

MECO	Main Engine Cut Off
M_f	Final Mass (kg)
M_o	Initial Mass (kg)
NASA	National Aeronautics and Space Administration
O_2/H_2	Oxygen/Hydrogen
$O_2/RP-1$	Oxygen/Kerosene
STS	Space Transportation System
Greek Symbols	
ΔV	Velocity Change (km/s)

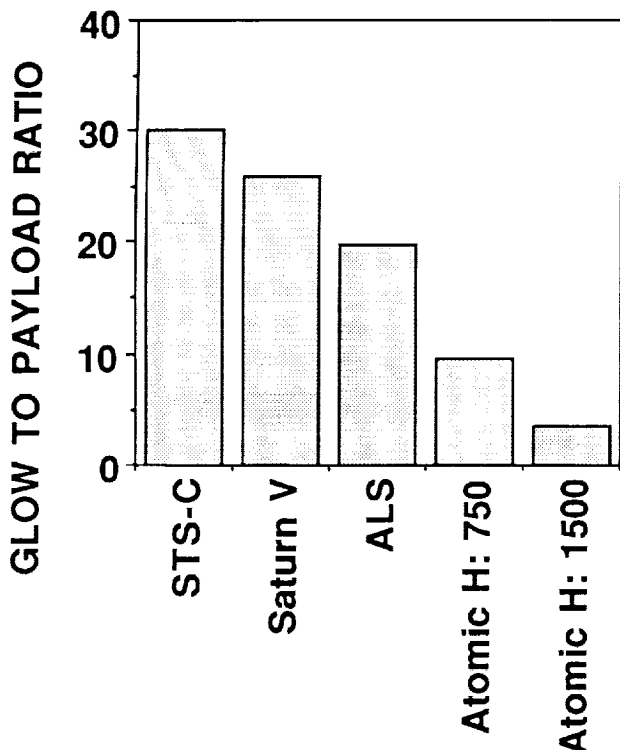
Introduction

In the development of NASA advanced launch vehicle designs, the need for increased payload delivery to orbit, increased reliability and reduced launch cost are crucial considerations. New technologies are being studied for the new vehicles such as the Advanced Launch System and the Shuttle-C (Refs. 1, 2, 3 and 4). These technologies include lightweight tankage and structures, avionics, aerothermodynamics, automated production facilities, operations and rocket engines.

Additional performance increases will be possible with the use of high-energy propellant combinations. Both increases in the propellant I_{sp} and increases in the propellant density are methods of improving the launch vehicle's performance. Many possible propellant combinations that can produce high I_{sp} are being studied both experimentally and theoretically. These studies are underway as part of the United States Air Force High Energy Density Materials (HEDM) Program (Ref. 5) and the NASA-Lewis Research Center Advanced Concepts Program.

One propellant that can provide increased I_{sp} is atomic hydrogen. In this paper, the potential benefits and the technology advancements that are required for the successful use of atomic hydrogen as a propellant are discussed. Using atomic hydrogen will require new propellant production and storage facilities. These new facility and production requirements must be contrasted with the significant performance capability of the new propellant.

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PROPULSION TECHNOLOGY

Figure 1. GLOW to Payload Ratio for Launch Vehicles

Advanced Launch Vehicle Propulsion

The current designs for the ALS and the Shuttle-C incorporate new technologies in the engines, propellant storage and feed systems and the launch operations. These advanced technologies, however, provide a small performance increase over the current state of the art in launch vehicle propulsion. Figure 1 contrasts the ratio of the GLOW to the payload delivered to Low Earth Orbit (LEO). A Shuttle-C ratio is 30. The STS-C payload mass (68,000 kg) does not include the cargo element (the payload carrier and boattail with Space Shuttle Main Engines). The ALS has an improved performance over the Saturn V (Ref. 6); a ratio of 20 and 26, respectively. An atomic hydrogen launch vehicle at an I_{sp} of 750 and 1500 $lb_f\text{-s}/lb_m$ is also shown. With atomic hydrogen, the ratio of GLOW to LEO payload is reduced to 9.5 and 3.4. This is 48 to 17 percent of that required by the state of the art ALS vehicles. By using a propellant such as atomic hydrogen, the mass of the launch vehicle can be reduced. These reductions in launch vehicle mass can be translated into smaller launch facilities, easier operations with the smaller launch vehicle stages and components and potentially lower overall costs for the advanced atomic hydrogen vehicle.

The comparison in Figure 1 is affected by several factors. For example, the Saturn V was a three stage vehicle delivering 113.4 metric tons to LEO. The STS-C delivers 68

metric tons to LEO and only has two stages. The ALS and the atomic hydrogen vehicles all deliver 96 metric tons. These comparisons are used only to contrast the overall performance of various launch systems.

In the analyses presented in the succeeding sections, several figures of merit will be used to compare the upper stages and the launch vehicles. Each vehicle has a different set of constraints and therefore a different measure of performance. For the upper stages, the figure of merit will be the injected mass (or payload) delivered to a injection energy. For the launch vehicles the GLOW will be the figure of merit.

Atomic Hydrogen Propellants

Atomic hydrogen is a free-radical propellant (Ref. 7). A very high energy can be released upon recombination of the hydrogen atoms. The theoretical energy release is 52.2 kcal/g. For a rocket propulsion system, this energy density implies an I_{sp} of 1900 $lb_f\text{-s}/lb_m$. Past studies have considered atomic hydrogen as a propellant for very high I_{sp} propulsion systems (Refs. 7, 8 and 9). These studies used atomic hydrogen for upper stages of launch vehicles.

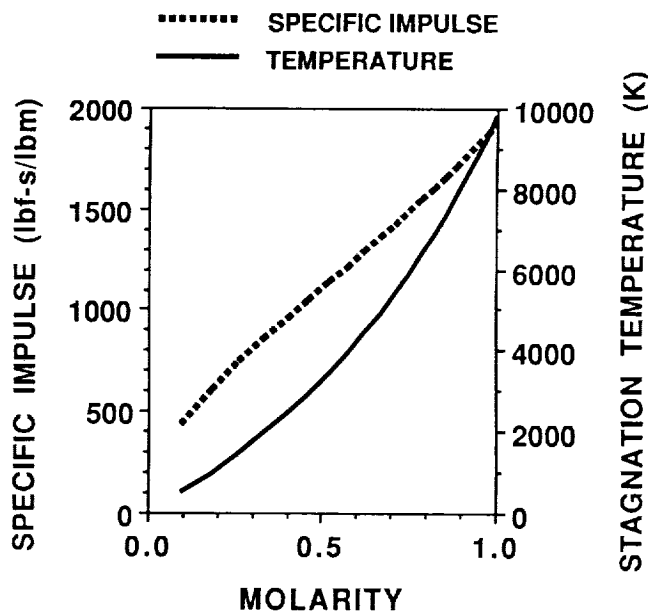


Figure 2. Atomic Hydrogen Specific Impulse

Propulsion Performance and Specific Impulse

Figure 2 depicts the I_{sp} of this propellant. The corresponding stagnation temperature is also provided. The I_{sp} is presented as a function of the molarity of the atomic hydrogen. At a 750- $lb_f\text{-s}/lb_m$ I_{sp} , the reaction temperature is 1,500 K. At an I_{sp} of 1,500 $lb_f\text{-s}/lb_m$, the stagnation temperature reaches 6000 K. These two I_{sp} s were used as examples of the propellant performance.

The I_{sp} in Figure 2 is shown as a function of the molarity of the atomic hydrogen. The molarity is:

$$M = \text{moles H} / (\text{moles H} + \text{moles H}_2)$$

where:

M Molarity

The molecular weights of H_2 and atomic hydrogen are 2.0158 g/mole and 1.0079 g/mole, respectively. For a molarity of 0.266, the weight fraction of atomic hydrogen would be 0.154 or 15.4 percent atomic hydrogen in the H_2 matrix. To produce a 1500-lb_f-s/lb_m I_{sp} , the molarity must be 0.761 or a weight fraction of 61.5 percent atomic hydrogen in the solid H_2 matrix.

The I_{sp} is estimated using (Ref. 10)

$$I_{sp} = 265 (m_H Q)^{0.5}$$

where:

I_{sp} Specific Impulse (lb_f-s/lb_m)

m_H mass fraction of atomic hydrogen

Q Energy Release (52.2 kcal/g)

The stagnation temperature is calculated using (Ref. 9):

$$T_0 = MW (I_{sp} * 27.4)^2$$

where:

T_0 Stagnation Temperature (K)

MW Exhaust Molecular Weight

Volume-Constrained Upper Stages

As part of the Space Transportation System (STS), a high-energy upper stage is required for placing payloads into high earth orbits and onto planetary trajectories. Because the Centaur is unavailable as an option for planetary missions, the Inertial Upper Stage (IUS) has been used as the primary STS upper stage. For a short trip time, many planetary missions require a high injection energy (C_3). Atomic hydrogen has been studied for use in a launch vehicle upper stage (Ref. 8). In this section, the performance of an atomic hydrogen upper stage will be discussed for the STS-C.

Mission Analysis. The figure of merit for comparing upper stages is the injected mass. This is the total mass delivered to a specific C_3 . The C_3 is defined as:

$$C_3 = ([\mu/r_o]^{0.5} + \Delta V)^2 - 2\mu/r_o$$

where:

C_3 Injection Energy (km²/s²)

ΔV Velocity Change (km/s)

μ Earth's Gravitational Constant (398601.3 km³/s²)

r_o Orbital Radius (km)
or 6378.14 km + Orbital Altitude (km)

The orbital altitude for the upper stages described in this paper was 241 km (130 nautical miles).

Upper Stage Figures of Merit. High performance for an upper stage can be defined in two ways: increased injected mass or increased C_3 . Increasing the injected mass allows the upper stage to deliver added payload to its target. By increasing the C_3 , the upper stage can provide a faster trip to the planets. Both of these benefits, higher injected mass and higher C_3 , must be traded for each mission. The Galileo mission is a case in point. The original mission design included an injection toward Jupiter with a C_3 of 79.2 km²/s² using a Centaur G-Prime (Ref. 11). The trip time to Jupiter was 1.5 years. With the IUS, the spacecraft was launched at a C_3 of 17 km²/s² (Ref. 12). The trip time to Jupiter was extended to 6.5 years.

Upper Stage Design Constraints. Using advanced propulsion for these upper stages can improve the performance of the STS for many high energy missions. Table I provides the I_{sp} s of the upper stages. Two high- I_{sp} O_2/H_2 propulsion systems and two atomic hydrogen system were analyzed as possible IUS replacements. For the O_2/H_2 systems, an existing Centaur G-Prime engine and an advanced engine were considered.

Table I
Propulsion System Specific Impulse

System	I_{sp} (lb _f -s/lb _m)
O_2/H_2 (Centaur Class)	446.4
Advanced O_2/H_2 (STE)	480
Atomic Hydrogen	750, 1500

An analysis was conducted for an atomic hydrogen vehicle constrained to the volume of the Centaur G-Prime in the STS cargo bay (Ref. 8). The performance of this vehicle for planetary missions was poor when compared to the then-currently baselined oxygen/hydrogen (O_2/H_2) STS-Centaur G-Prime upper stage (Ref. 8). Though the I_{sp} of the atomic hydrogen stage was higher than the Centaur, the total mass of propellant that could be carried in the STS bay was limited. The cases of a volume-limited and a mass-limited atomic hydrogen upper stage were considered. The total propellant loads in the two types of stages were 5500 kg and 7973 kg, respectively (Ref. 8). The I_{sp} of both upper stages was 740 lb_f-s/lb_m.

The volume limitation imposed by the STS and the Centaur volume placed very severe constraints on the atomic hydrogen upper stage design. No performance advantage was

gained using atomic hydrogen in this configuration. Also, the mass of the thermal control system and the magnetic field generator for the propellant storage system was carried in the orbiter bay. Their total mass was considered comparable to the Airborne Support Equipment (ASE) for the Centaur. The mass of this added ASE also reduced the mass available for the atomic hydrogen stage.

If the volume of the upper stage were not restricted to the fixed volume of the STS cargo bay, the performance of that vehicle would be enhanced. In this paper, an atomic hydrogen stage was designed to conform to the volume and mass constraints of the STS-C payload element (Ref. 4). The STS-C has a substantially longer cargo bay and can alleviate some of the volume constraints of the current Space Shuttle.

Though the O_2/H_2 stages can use the maximum STS-C payload mass capability, the volume of the payload element restricts the atomic hydrogen stage's tank length (and thus the total mass of propellant) that can be accommodated by the STS-C. Thus, the O_2/H_2 stages in the STS-C were mass limited. The stages using atomic hydrogen were volume limited. The total launch masses for the atomic hydrogen stages were significantly lower than the 68,000-kg payload of the STS-C.

In the performance calculations, the O_2/H_2 stages were sized for a maximal propellant load. This design point corresponds to an injected mass of 100 kg. At all higher injected masses, the O_2/H_2 stage must have propellant offloaded from the tanks. With the atomic hydrogen stage, the stage's propellant density is sufficiently low that the stage is fully loaded with propellant for the full range of the injected masses.

In this analysis, the maximum total mass delivered to LEO (the stage, propellant, payload, adapter and ASE) was 68,000 kg (Ref. 4). The ASE mass was 4109 kg (Ref. 13). The total dry mass was fixed and propellant mass for the upper stages was allowed to vary over the range of injected masses. The propulsion mass-scaling equation for the stage was:

$$m_{dry} = 1211.66 + 0.3160 m_p \text{ (kg)}$$

where:

m_{dry} Stage Burnout Mass (kg)

m_p Propellant Mass (kg)

The propellant tank was 4 meters in diameter and 18.7 meters long. This tank length is accommodated by the 25-meter long STS-C payload element cargo bay (Ref. 4). This tank also holds the maximal propellant load for the atomic hydrogen upper stage: 18,300 kg. This propellant mass was selected based on the volume and length constraint of the cargo bay. The remainder of the bay length

accommodates the payload; this length is 6.3 meters (20 feet).

Two types of cryogenic stages were considered. An oxygen/hydrogen upper stage using an engine performance that is similar to the engines of the Centaur G-Prime was the first type of vehicle ($I_{sp} = 446.4 \text{ lb}_f\text{-s/lb}_m$). A high-performance upper stage using a Space Transfer Engine (STE, Ref. 14) was also analyzed. The I_{sp} of this vehicle was 480 $\text{lb}_f\text{-s/lb}_m$. The propulsion mass-scaling equation for both types of stages was:

$$m_{dry} = 350.55 + 0.1598 m_p \text{ (kg)}$$

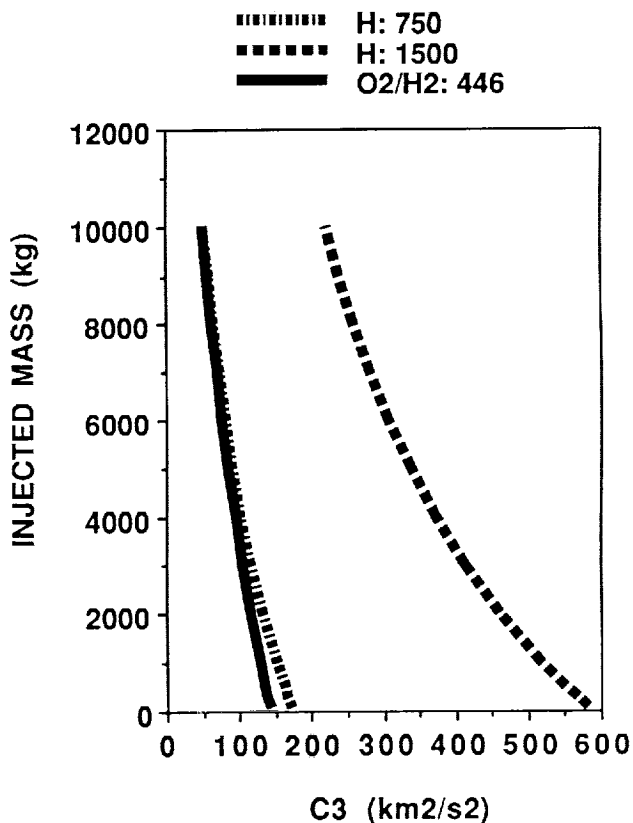


Figure 3. Upper Stage Performance:
 O_2/H_2 Stage (446.4 $\text{lb}_f\text{-s/lb}_m$ I_{sp})
and Atomic H

Upper Stage Results. Figure 3 compares the injected mass capability for two atomic hydrogen upper stages with a stage that has the I_{sp} of the Centaur G-Prime. Because the O_2/H_2 stage was designed for the STS-C cargo bay, it has a substantially higher propellant load: up to 54,700 kg rather than 20,300 kg for the Centaur. The C_3 ranges from 0 to 600 km^2/s^2 . A C_3 of 10 to 86 km^2/s^2 is representative of that required for many past, currently-planned and future planetary missions (Refs. 11, 12 and 13).

Using atomic hydrogen at an I_{sp} of 750 $\text{lb}_f\text{-s/lb}_m$ provides only a small performance benefit. It provides a benefit for missions requiring a C_3 greater than 50 km^2/s^2 . It can

deliver 6200 kg to a C_3 of $80 \text{ km}^2/\text{s}^2$ while the O_2/H_2 stage can deliver over 5700 kg. This C_3 is representative of an outer planet mission on a direct injection (no Earth or Venus Gravity Assist maneuvers required). Only when operating the system at a $1500\text{-lb}_f\text{-s}/\text{lb}_m$ I_{sp} does atomic hydrogen provide a significant performance advantage over the O_2/H_2 stage. At a C_3 of $80 \text{ km}^2/\text{s}^2$, the atomic hydrogen upper stage ($I_{sp} = 1500 \text{ lb}_f\text{-s}/\text{lb}_m$) is able to inject over 26,500 kg.

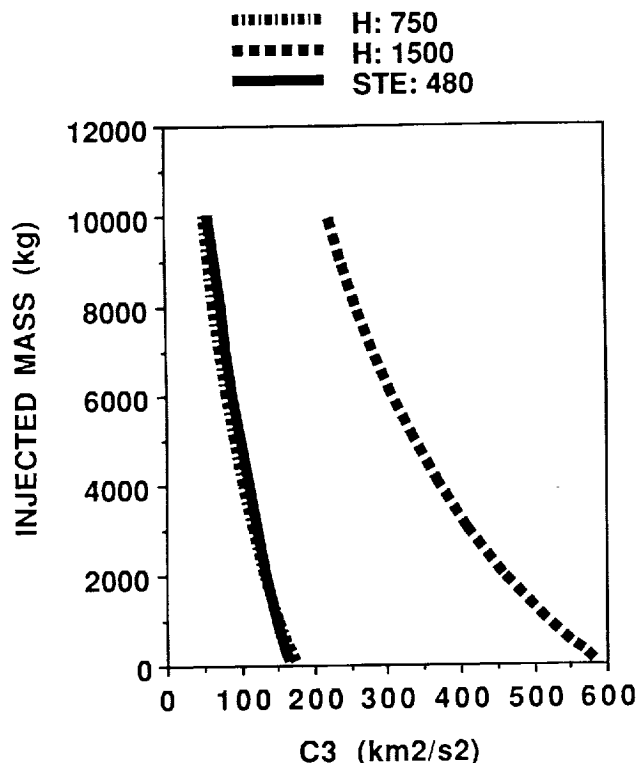
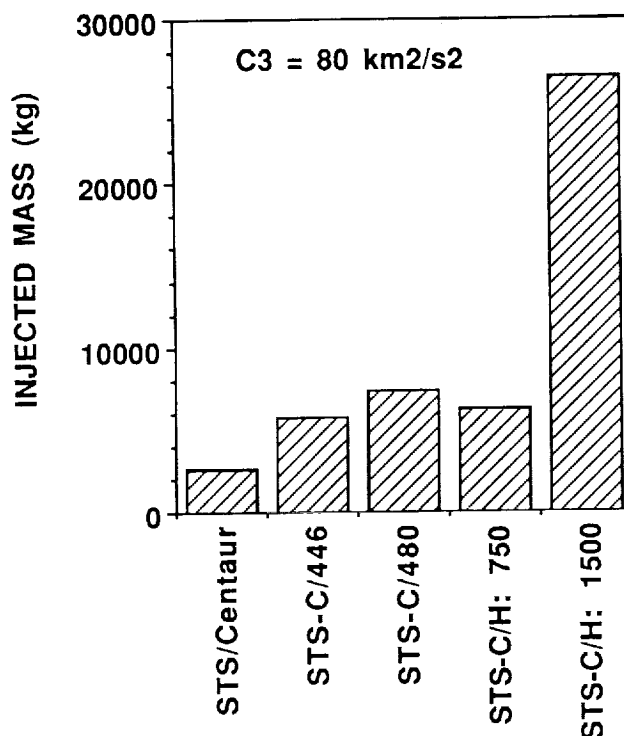


Figure 4. Upper Stage Performance: STE Stage and Atomic H

Figure 4 provides the performance comparison of the STE-based stage with atomic hydrogen. In sizing the STE stage, the full 68,000-kg payload capability of the STS-C was assumed. To fit within the volume and mass limitations of the STS-C, the hydrogen tank diameter was 4.5 meters and the oxygen tank diameter was 3.05 meters. The maximal propellant mass for the stage is the same as that with the lower I_{sp} stage: 54,700 kg.

The STE stage provides a similar performance to the atomic hydrogen upper stage (with a $750\text{-lb}_f\text{-s}/\text{lb}_m$ I_{sp}). For near-term upper stage applications, an advanced O_2/H_2 upper stage would provide the potential performance of atomic hydrogen. As with the previous analysis, only when the atomic hydrogen I_{sp} is greater than $750 \text{ lb}_f\text{-s}/\text{lb}_m$ will it provide a benefit over advanced O_2/H_2 propulsion.

This STE stage does provide a large payload benefit over the O_2/H_2 stage presented in Figure 3. At a C_3 of $80 \text{ km}^2/\text{s}^2$, the injected mass is 7,300 kg. This is 1,600 kg more than the stage with a $446.4\text{-lb}_f\text{-s}/\text{lb}_m$ I_{sp} .



UPPER STAGE TECHNOLOGY

Figure 5. Upper Stage Injected Mass: $C_3 = 80 \text{ km}^2/\text{s}^2$

Oxygen/Hydrogen Propulsion Benefits. It should be noted that the Centaur G-Prime that was planned for the current STS had significantly lower performance than either of the O_2/H_2 stages discussed above. Figure 5 compares the systems discussed above: the three O_2/H_2 options and the two atomic hydrogen stages. The injected masses for the cryogenic stages in the STS-C were more than doubled over the Centaur. Aboard the current STS, the Centaur G-Prime was only able to inject 2600 kg to a C_3 of $80 \text{ km}^2/\text{s}^2$. Thus, the STS-C with an improved large cryogenic stage can provide a considerable benefit to the planetary program.

Upper Stage Observations. Future atomic hydrogen propellants may provide an important performance advantage over chemical propulsion upper stages. This high performance for an upper stage is only attainable for high densities of atomic hydrogen. The high performance level of $1500 \text{ lb}_f\text{-s}/\text{lb}_m$ should only be considered for far-term missions. An extensive program of basic research and development is needed to determine whether such densities are feasible and producible.

Launch Vehicle Performance Analysis

The significant performance penalties associated with a volume-constrained upper stage will be relaxed in the design of a launch vehicle. The major volume constraints in a launch vehicle are determined by the ability to easily manufacture its elements

and to transport them to and about the launch site. Its volume is much less constrained than an upper stage in the STS or STS-C cargo bay. Also, the mass and volume associated with the refrigeration facility and the magnetic field coils for storing atomic hydrogen can be left at the launch site. By placing the mass of these facilities on the ground, the launch vehicle will no longer be constrained to "pay" the mass and volume penalties associated with the STS.

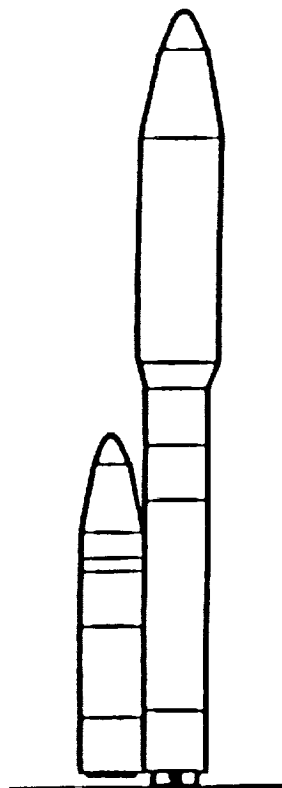


Figure 6. ALS Configuration Using O₂/H₂

Current ALS Vehicle Designs. Figure 6 depicts a possible configuration for the ALS. Many different design concepts are being investigated. In this analysis, two different payloads to Low Earth Orbit (LEO), each with a different propellant combination was considered.

One design used an O₂/H₂/RP-1 booster with an O₂/H₂ main core section. Hydrogen from the core was used in the booster propulsion system. The booster I_{sp} was 356.6 lb_f-s/lb_m (vacuum performance). Each of the five engines delivered a thrust of 676,770 lb_f.

A module on the booster and the core containing the propulsion system and avionics was recovered and reused. In the core section, three Space Shuttle Main Engines provided an I_{sp} of 452.9 lb_f-s/lb_m. Each had a thrust of 470,000 lb_f. The payload delivered to orbit was 43,000 kg. It had a GLOW of 1,192,000 kg. In the second design, the vehicle used O₂/H₂ in the core

and boosters. Its payload to orbit was 96,000 kg and its GLOW was 1,891,000 kg.

Atomic Hydrogen Mission Analysis. The atomic hydrogen launch vehicle design used two stages. Each stage delivered one half of the total 9.7-km/s ΔV. This ΔV included 9.2 km/s (Refs. 15 and 16) for the primary ascent to orbit and the typical gravity losses and a 0.5 km/s ΔV for other additional gravity losses (drag due to differing configurations and very high accelerations) of the launch vehicle. The second stage also delivered an additional 50 m/s after it burned out for a payload separation maneuver.

Propulsion System Mass Scaling. For the launch vehicle, the atomic hydrogen was stored in a solid H₂ matrix. This matrix was stored at 4 K. Its density was 88 kg/m³ (Ref. 17). The propellant tank operating pressure was 30 psia and the maximum expected operating pressure was 50 psia. A 6.1-meter diameter tank was used and the feed system was pressure-fed. The propellant residual and holdup mass was 1.5 percent of the total propellant mass. An ullage volume of 6 percent was used. The engine for each stage had a 60:1 expansion ratio nozzle. The chamber pressure for this engine was 30 psia. The propulsion mass-scaling equation for the stage was:

$$m_{dry} = 10940 + 0.2883 m_p \text{ (kg)}$$

Table II
Atomic Hydrogen Launch Vehicle
Mass Summary
I_{sp} = 750 lb_f-s/lb_m

Element	Mass (kg)
Payload	95,708
Fairing	7,648
Payload Adapter	5,440
Stage 2:	
Tankage	15,039
Thermal Control	12,134
Engine and Feed System	10,000
Structure	10,777
Residuals and Holdup	2,345
Contingency	5,030
Propellant	153,963
Interstage Adapter	16,741
Stage 1:	
Tankage	43,436
Thermal Control	34,576
Engine and Feed System	10,000
Structure	30,901
Residuals and Holdup	6,722
Contingency	12,563
Propellant	441,438
Total	914,461

Also included in the launch vehicle mass-scaling equation was the thermal control system with insulation and a Thermodynamic Vent System/Vapor-Cooled Shield (TVS/VCS), the structure and the propellant feed system. Table II provides a mass summary for the two-stage vehicle.

As an added mass apart from the propulsion mass-scaling equation, a 7648-kg payload fairing or shroud was also provided on the launch vehicle. It was carried all the way to orbit.

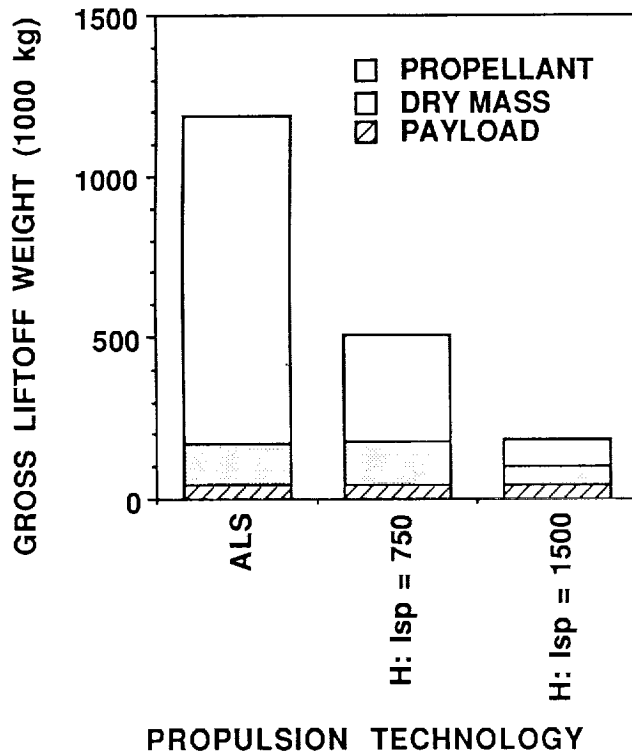


Figure 7. Launch Vehicle GLOW:
43,000-kg LEO Payload

Launch Vehicle Results. Figure 7 compares the ALS and the atomic hydrogen launch vehicles GLOW for the 43,000-kg payload. Table III lists the GLOWs for both vehicle designs. The mass savings for the atomic hydrogen vehicle with an I_{sp} of 750 lb_f-s/lb_m was 58 percent. An 85-percent GLOW reduction was achieved with a 1500- lb_f-s/lb_m I_{sp} . In the same comparison for the 96,000-kg payload, the mass savings for the 750- lb_f-s/lb_m I_{sp} is over 52 percent. The GLOW reduction was 83 percent at an I_{sp} of 1500 lb_f-s/lb_m .

The analyses of both the upper stages' and the launch vehicles' performance shows that the highest benefit can be derived from atomic hydrogen in a launch vehicle. At a 750- lb_f-s/lb_m I_{sp} , the large GLOW reductions (52 to 58 percent) that are achieved can potentially reduce the cost of Earth to orbit operations. Additional performance increases to 1500 lb_f-s/lb_m can further

Table III
Launch Vehicle GLOW Comparison

System	GLOW (kg)
Payload: 43,000 kg	
ALS	1,191,900
Atomic Hydrogen: 750	504,095
1500	183,267
Payload: 96,000 kg	
ALS	1,891,500
Atomic Hydrogen: 750	914,461
1500	326,879

reduce the GLOW by 82 to 85 percent over the ALS GLOW.

Engine and Nozzle Design. The performance levels for the atomic hydrogen vehicle are based on an engine with a 30-psia chamber pressure. This low pressure for a launch vehicle requires a large nozzle. A 10,000-kg mass was allocated for the engine on each stage. This estimate will be refined as more detailed designs for the engine system are developed.

For the 750- lb_f-s/lb_m I_{sp} vehicle, the stagnation temperature of the atomic hydrogen recombination is 1500 to 2000 K. This relatively low temperature is comparable to the current state of the art propulsion engine temperatures. At the high temperature predicted for the higher 1500- lb_f-s/lb_m I_{sp} , the stagnation temperature is 6000 K. This high temperature and I_{sp} nozzle may require a combination of regenerative and transpiration cooling. Additional performance analyses are planned to determine the effect of chamber pressure and temperature on the engine design.

Launch Vehicle Thrust Level. An engine thrust level for the first and second stages of the launch vehicles are listed in Table IV. The burn rate for the 750- lb_f-s/lb_m I_{sp} launch vehicle design (96,000-kg payload) is 1340 kg/s. This rate was computed using an initial thrust to weight (T/W) for the vehicle at liftoff of 1.1. At an I_{sp} of 1500 lb_f-s/lb_m , the mass flow is 240 kg/s.

In applying atomic hydrogen to propulsion, the very fast recombination rate must be considered. A recombination rate of 210 cm/s is predicted for atomic hydrogen (Ref. 10). This rate is analogous to (and substantially higher than) the burn rate of solid propellants. A typical solid burn rate for STS-C is 0.947 cm/s (0.373 in/s, Ref. 4). This high recombination rate can produce very high accelerations for the launch vehicle.

To control the vehicle thrust level, the propellant can be segmented. The segmenting will prevent the neighboring propellant from recombining (Ref. 8). One possible design would introduce a "pelletized" propellant

Table IV
Atomic Hydrogen
Launch Vehicle Thrust Levels

System	Thrust Level (lb _f)
Payload: 43,000 kg	
750 lb _f -s/lb _m	
Stage 1	1,222,000
Stage 2	414,000
1500 lb _f -s/lb _m	
Stage 1	445,000
Stage 2	244,000
Payload: 96,000 kg	
750 lb _f -s/lb _m	
Stage 1	2,218,000
Stage 2	771,000
1500 lb _f -s/lb _m	
Stage 1	793,000
Stage 2	456,000

Initial Thrust to Weight = 1.1

into the "combustion" or recombination chamber. The rate of recombination of the total propellant load can therefore be controlled and control of the vehicle thrust level is more easily achieved.

In Ref. 8, an insulator was used to isolate the individual atomic hydrogen propellant elements from each other. The materials selected were hafnium dioxide and zirconium dioxide. This insulator was selected for its thermal properties and its ability to maintain the temperature of the propellant element below 1 K for a short duration. A derivative of this type of approach may be used to inhibit the propellant recombination.

The launch vehicle will require very large propellant elements. If the propellant burn rate is 1340 kg/s, and if one element is burned per second, the number of elements required will be:

$$\frac{441,440 \text{ kg of propellant}}{1340 \text{ kg per element}} = 330 \text{ elements}$$

for the first stage of the 750-lb_f-s/lb_m I_{sp} vehicle (96,000-kg payload). This type of segmenting, however, may ease the propellant production, transportation and operations. If the propellant is fabricated in smaller elements, the size and cost of the production facility may be reduced. A large facility to produce atomic hydrogen in the 100,000-kg propellant tanks would no doubt be more massive than one with the requirement to produce smaller elements with an individual mass of 1000 kg.

System-Level Design Issues

To deliver the propulsion performance discussed above, several challenging technologies will have to be developed. The production, transportation and long-term storage of large quantities of atomic hydrogen will be needed. Each of these areas and their effect on the launch vehicle processing is discussed below.

Production and Storage Methods

Currently, no methods of producing or storing large amounts of atomic hydrogen exist. A series of preliminary studies and experiments on the production methods were conducted from the 1950's through the 1980's (Refs. 7, 9, 10, 18 and 19). These past research programs estimated the storage density of atomic hydrogen and proposed storage methods using solid or gaseous H₂ as a storage matrix.

There are two storage methods for atomic hydrogen. One uses a solid hydrogen matrix (Refs. 10, 18 and 19). Atomic hydrogen is formed in the solid hydrogen. The second method is called Bose-Einstein Condensation (BEC, Ref. 20).

In the first method, the atomic hydrogen will be placed in the hydrogen matrix by one of several methods: electron beams, radiofrequency discharge and radioactive decay of tritium (Ref. 21). Current experiments (Ref. 21) are using tritium decay for the atomic hydrogen production. The specific method used for producing large quantities will depend on the cost and the ease of process control.

The highest storage density for atomic hydrogen has been achieved in a solid hydrogen matrix (Ref. 21). This matrix is a solid at a temperature of 4 to 16 K. The achieved density is 0.5 to 1 percent of atomic hydrogen (by weight) in the solid hydrogen. As discussed above, this storage density is substantially lower than that required for launch vehicle propulsion. Future experiments will determine if there is a mechanism for increasing this density to the needed levels.

With the second method, Bose-Einstein Condensation, the storage density that results is very low. This is because the atomic hydrogen is formed gaseous matrix and then cooled (Ref. 20). The density of atomic hydrogen that is produced with this method can be several orders of magnitude lower than using a solid hydrogen matrix. Because of the low storage density produced, it has been rejected as a useful method for storing atomic hydrogen for propulsion.

Kapitza Effect and Low Temperatures

Storing the atomic hydrogen at temperatures lower than 4 K has been considered (Refs. 10, 19 and 20). These lower temperature have

the potential for increasing the storage time (time without recombination of the atomic hydrogen). A temperature of 4 K was chosen to avoid thermal problems associated with the Kapitza effect. This effect results in an increased thermal resistance at temperatures below 4 K. At temperatures below 4 K, the transmission of energy is not controlled by conduction but by an acoustic coupling (Ref. 22). As the temperature is reduced, the resistance increases. Attaining a very low temperature is therefore extremely difficult. Operating the storage facility at 4 K will obviate this problem.

Long-Term Storage and Transfer

Magnetic Field Strength. A high magnetic field has been proposed as a way of extending the storage time of atomic hydrogen (Refs. 10, 18 and 19). A 30-kilogauss magnetic field was predicted for atomic hydrogen storage (Ref. 18). This magnetic field strength is a function of the storage time and the storage temperature. Research is continuing on the effect of the fields on inhibiting the recombination.

At the launch site, a very long storage time of months will be needed. The propellant will be in deep cryogenic storage. Because the propellant loads are large, the magnet and the refrigeration facilities will be substantial. The first and second stages of the 750-lb_f-s/lb_m I_{sp} vehicle require propellant loads of 441,440 and 154,000 kg, respectively (96,000-kg payload).

An important point to consider is that the magnetic field coils do not have to be part of the launch vehicle. Atomic hydrogen does require the use of intense magnetic fields for long-term storage. To use atomic hydrogen for launch vehicle propulsion, the propellant must be prevented from recombining for the short period from launch to achieving orbit. Storage times of minutes to hours have been achieved (Ref. 18). For a launch vehicle, the total vehicle firing time is only 10 to 15 minutes. Thus, the predicted and demonstrated storage times are sufficient to allow the vehicle to reach orbit.

Propellant Operations and Facilities. A 4-K temperature for the launch vehicle will require new facilities. This temperature will require large amounts of liquid helium at the launch site. It will be used for cooling the superconducting magnetic field coils and for producing and maintaining the solid hydrogen matrix.

Atomic hydrogen may have to be produced at the launch site. Transportation of the propellant from a remote site may require the movement of large magnetic bottles. The very high field strengths of the bottles would require large massive surface- or ship-based transporters. As discussed above, a production facility for small propellant "elements" may be an option. This facility may be small given the reduced size of the atomic hydrogen elements (1000 kg).

Transporting large numbers of smaller elements may be more cost effective than moving large single 100,000 kg propellant loads or elements.

Conclusions

Atomic hydrogen propulsion systems can potentially produce a very high I_{sp}. This high performance level can significantly reduce the launch mass of future launch vehicles. Using atomic hydrogen with an I_{sp} of 750 and 1500 lb_f-s/lb_m, very large GLOW reductions over the current ALS launch vehicle designs are possible.

Upper stages using atomic hydrogen can also be a benefit to the NASA planetary program and for orbital transfer. Only stages with an I_{sp} significantly greater than 750 lb_f-s/lb_m, however, will provide a significant performance advantage of O₂/H₂ propulsion upper stages. Constraining the stage to the volume of the STS-C cargo bay restricts the atomic hydrogen stage performance at the lower I_{sp}s.

This free-radical propellant brings with it a set of unique challenges for the rocket propulsion designer. Producing and storing atomic hydrogen for propulsion will require both low cryogenic temperatures (near 4 K) and high magnetic fields (as high as 30 kilogauss or 3 Tesla). Large magnet and refrigeration facilities to produce and store the propellant will be needed. To produce the atomic hydrogen either tritium decay, radiofrequency excitation or electron beams will be needed.

A significant amount of systems design will be required to determine the final "best" design for the atomic hydrogen launch vehicle and its support facilities. Additional analyses of these systems will provide insight into the complexity of transporting and storing atomic hydrogen in a realistic, operational environment.

Clearly, a considerable amount of both basic technology and basic physics research is required before the possible benefits of atomic hydrogen can be fully determined. There may be significant benefit for a launch vehicle or an upper stage, but the potential must be matched by demonstrations of high storage density and controllability as a rocket propellant.

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16. Abstract <p>An analysis of several atomic hydrogen launch vehicles was conducted. A discussion of the facilities and the technologies that would be needed for these vehicles is also presented. The Gross Liftoff Weights (GLOW) for two systems were estimated; their specific impulses (I_{sp}) were 750 and 1500 lb_f-s/lb_m. The atomic hydrogen launch vehicles were also compared to the currently planned Advanced Launch System design concepts. Very significant GLOW reductions of 52 to 85 percent are possible over the Advanced Launch System designs. Applying atomic hydrogen propellants to upper stages was also considered. Very high I_{sp} (greater than 750 lb_f-s/lb_m) is needed to enable a mass savings over advanced oxygen/hydrogen propulsion. Associated with the potential benefits of high-I_{sp} atomic hydrogen are several challenging problems. Very high magnetic fields are required to maintain the atomic hydrogen in a solid hydrogen matrix. The magnetic field strength has been estimated to be 30 kilogauss (3 Tesla). Also the storage temperature of the propellant is 4 K. This very low temperature will require a large refrigeration facility for the launch vehicle. The design considerations for a very high recombination rate for the propellant are also discussed. A recombination rate of 210 cm/s is predicted for atomic hydrogen. This high recombination rate can produce very high acceleration for the launch vehicle. Unique insulation or segmentation to "inhibit" the propellant may be needed to reduce its recombination rate.</p>					
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