Atomic Hydrogen as a Launch Vehicle Propellant

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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 \( I_p \) were 750 and 1500 \( \text{lb}_s/\text{lbf} \). 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 \( I_p \) (greater than 750 \( \text{lb}_s/\text{lbf} \)) is needed to enable a mass savings over advanced oxygen/hydrogen propulsion.

Associated with the potential benefits of high-\( I_p \) 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 \( \text{cm}/\text{s} \) 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

<table>
<thead>
<tr>
<th>ME</th>
<th>MECO</th>
<th>Main Engine Cut Off</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mt</td>
<td>Final Mass (kg)</td>
<td></td>
</tr>
<tr>
<td>M0</td>
<td>Initial Mass (kg)</td>
<td></td>
</tr>
</tbody>
</table>

NASA | National Aeronautics and Space Administration |
O2/H2 | Oxygen/Hydrogen |
O2/RP-1 | Oxygen/Kerosene |
STS | Space Transportation System |

Greek Symbols
\( \Delta V \) | 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 \( I_p \) and increases in the propellant density are methods of improving the launch vehicle's performance. Many possible propellant combinations that can produce high \( I_p \) 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 \( I_p \) 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 facilities and production requirements must be contrasted with the significant performance capability of the new propellant.

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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 \( I_p \) of 750 and 1500 \( \text{lbf} \cdot \text{s} / \text{lb} \) 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 \( I_p \) of 1900 \( \text{lbf} \cdot \text{s} / \text{lb} \). Past studies have considered atomic hydrogen as a propellant for very high \( I_p \) propulsion systems (Refs. 7, 8 and 9). These studies used atomic hydrogen for upper stages of launch vehicles.
The $I_{sp}$ in Figure 2 is shown as a function of the molarity of the atomic hydrogen. The molarity is:

$$M = \frac{\text{moles H}}{\text{moles H + moles H}_2}$$

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/s/lb$_o$ $I_{sp}$, 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)

$$I_{sp} = 265 \left( \frac{m_h}{Q} \right)^{0.5}$$

where:

$I_{sp}$ Specific Impulse (lb$_f$-s/lb$_o$)

$m_h$ mass fraction of atomic hydrogen

$Q$ Energy Release (52.2 kcal/g)

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

$$T_0 = MW \left( I_{sp} \times 27.4 \right)^2$$

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:

$$C_3 = (\left( \frac{\mu}{r_o} \right)^{0.5} + \Delta V)^2 - 2 \mu/r_o$$

where:

$C_3$ Injection Energy (km$^2$/s$^2$)

$\Delta V$ Velocity Change (km/s)

Earth's Gravitational Constant (398601.3 km$^3$/s$^2$)

$r_o$ 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 km$^2$/s$^2$ 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 km$^2$/s$^2$ (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 systems 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>
<thead>
<tr>
<th>System</th>
<th>$I_{sp}$ (lb$_f$-s/lb$_o$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O$_2$/H$_2$ (Centaur Class)</td>
<td>446.4</td>
</tr>
<tr>
<td>Advanced O$_2$/H$_2$ (STE)</td>
<td>480</td>
</tr>
<tr>
<td>Atomic Hydrogen</td>
<td>750, 1500</td>
</tr>
</tbody>
</table>

An analysis was conducted for a high energy 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 stages 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$_o$.

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\textsubscript{2}/H\textsubscript{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\textsubscript{2}/H\textsubscript{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\textsubscript{2}/H\textsubscript{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\textsubscript{2}/H\textsubscript{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:

\[ m_{dry} = 1211.66 + 0.3160 m_p \]  

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 \( (I_p = 446.4 \text{ lb}_s/\text{lb}_m) \). A high-performance upper stage using a Space Transfer Engine (STE, Ref. 14) was also analyzed. The \( I_p \) of this vehicle was 480 lb\textsubscript{s}/lb\textsubscript{m}. The propulsion mass-scaling equation for both types of stages was:

\[ m_{dry} = 350.55 + 0.1598 m_p \]  

Figure 3. Upper Stage Performance: \( \text{O}_2/\text{H}_2 \) Stage (446.4 lb\textsubscript{s}/lb\textsubscript{m} \( I_p \)) 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 \( I_p \) of the Centaur G-Prime. Because the \( \text{O}_2/\text{H}_2 \) 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\textsuperscript{2}/s\textsuperscript{2}. A \( C_3 \) of 10 to 86 km\textsuperscript{2}/s\textsuperscript{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 \( I_p \) of 750 lb\textsubscript{s}/lb\textsubscript{m} provides only a small performance benefit. It provides a benefit for missions requiring a \( C_3 \) greater than 50 km\textsuperscript{2}/s\textsuperscript{2}. It can
deliver 6200 kg to a $C_3$ of 80 km/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-lbf-s/lbm $I_{sp}$ does atomic hydrogen provide a significant performance advantage over the $O_2/H_2$ stage. At a $C_3$ of 80 km/s$^2$, the atomic hydrogen upper stage ($I_{sp} = 1500$ lbf-s/lbm) is able to inject over 26,500 kg.

![Diagram](image)

**Figure 4. Upper Stage Performance:**

STE Stage and Atomic H

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 km/s$^2$, the injected mass is 7,300 kg. This is 1,600 kg more than the stage with a 446.4-lbf-s/lbm $I_{sp}$.

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**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 km/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 lbf-s/lbm 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 $\text{O}_2/\text{H}_2$](image)

**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 $\text{O}_2/\text{H}_2$ booster with an
$\text{O}_2/\text{H}_2$ main core section. Hydrogen from the
core was used in the booster propulsion
system. The booster $I_{sp}$ was 356.6 lb-sec/lb$_p$ (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-sec/lb$_p$.
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 $\text{O}_2/\text{H}_2$ in the core

### 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 $\Delta V$. This $\Delta V$ 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 $\Delta V$ 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 $\text{H}_2$ matrix. This matrix was
stored at 4 K. Its density was 88 kg/m$^3$
(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>
<thead>
<tr>
<th>Element</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload</td>
<td>95,708</td>
</tr>
<tr>
<td>Fairing</td>
<td>7,648</td>
</tr>
<tr>
<td>Payload Adapter</td>
<td>5,440</td>
</tr>
<tr>
<td>Stage 2:</td>
<td></td>
</tr>
<tr>
<td>Tankage</td>
<td>15,039</td>
</tr>
<tr>
<td>Thermal Control</td>
<td>12,134</td>
</tr>
<tr>
<td>Engine and Feed System</td>
<td>10,000</td>
</tr>
<tr>
<td>Structure</td>
<td>10,777</td>
</tr>
<tr>
<td>Residuals and Holdup</td>
<td>2,345</td>
</tr>
<tr>
<td>Contingency</td>
<td>5,030</td>
</tr>
<tr>
<td>Propellant</td>
<td>153,963</td>
</tr>
<tr>
<td>Interstage Adapter</td>
<td>16,741</td>
</tr>
<tr>
<td>Stage 1:</td>
<td></td>
</tr>
<tr>
<td>Tankage</td>
<td>43,436</td>
</tr>
<tr>
<td>Thermal Control</td>
<td>34,576</td>
</tr>
<tr>
<td>Engine and Feed System</td>
<td>10,000</td>
</tr>
<tr>
<td>Structure</td>
<td>30,901</td>
</tr>
<tr>
<td>Residuals and Holdup</td>
<td>6,722</td>
</tr>
<tr>
<td>Contingency</td>
<td>12,563</td>
</tr>
<tr>
<td>Propellant</td>
<td>441,438</td>
</tr>
<tr>
<td>Total</td>
<td>914,461</td>
</tr>
</tbody>
</table>
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.

<table>
<thead>
<tr>
<th>System</th>
<th>GLOW (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload: 43,000 kg</td>
<td></td>
</tr>
<tr>
<td>ALS</td>
<td>1,191,900</td>
</tr>
<tr>
<td>Atomic Hydrogen</td>
<td>750</td>
</tr>
<tr>
<td></td>
<td>1500</td>
</tr>
<tr>
<td>Payload: 96,000 kg</td>
<td></td>
</tr>
<tr>
<td>ALS</td>
<td>1,891,500</td>
</tr>
<tr>
<td>Atomic Hydrogen</td>
<td>750</td>
</tr>
<tr>
<td></td>
<td>1500</td>
</tr>
</tbody>
</table>

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-Ibf-s/lbm Isp 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-Ibf-s/lbm Isp, the stagnation temperature is 6000 K. This high temperature and Isp 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-Ibf-s/lbm Isp 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 Isp of 1500 Ibf-s/lbm, 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

<table>
<thead>
<tr>
<th>System</th>
<th>Payload (kg)</th>
<th>Thrust Level (lb, s/lb, m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>43,000</td>
<td></td>
</tr>
<tr>
<td>750 lb, s/lb, m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stage 1</td>
<td>1,222,000</td>
<td></td>
</tr>
<tr>
<td>Stage 2</td>
<td>414,000</td>
<td></td>
</tr>
<tr>
<td>1500 lb, s/lb, m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stage 1</td>
<td>445,000</td>
<td></td>
</tr>
<tr>
<td>Stage 2</td>
<td>244,000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>96,000</td>
<td></td>
</tr>
<tr>
<td>750 lb, s/lb, m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stage 1</td>
<td>2,218,000</td>
<td></td>
</tr>
<tr>
<td>Stage 2</td>
<td>771,000</td>
<td></td>
</tr>
<tr>
<td>1500 lb, s/lb, m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stage 1</td>
<td>793,000</td>
<td></td>
</tr>
<tr>
<td>Stage 2</td>
<td>456,000</td>
<td></td>
</tr>
</tbody>
</table>

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, s/lb, m 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-.s/1b_ I_p 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 store the propellant will be needed. 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.

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_p. This high performance level can significantly reduce the launch mass of future launch vehicles. Using atomic hydrogen with an I_p of 750 and 1500 lb-s/1b, 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_p significantly greater than 750 lb-s/Ibm will provide a significant performance advantage of O/H 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_p.

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.

References


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 ($I_p$) were 750 and 1500 lbf-s/lbm. 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 $I_p$ (greater than 750 lbf-s/lbm) is needed to enable a mass savings over advanced oxygen/hydrogen propulsion. Associated with the potential benefits of high-$I_p$ 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.