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Atomic Hydrogen Propellants: Historical Perspectives and Future Possibilities

Bryan Palaszewski
Lewis Research Center
Cleveland, Ohio

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Atomic Hydrogen Propellants: Historical Perspectives and Future Possibilities

Bryan Palaszewski*
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, OH

Abstract

Very high energy density, free-radical propellants such as atomic hydrogen may enable unique launch vehicle propulsion applications. Atomic hydrogen could deliver a specific impulse between 600 and 1500 lb_f-s/lb_m performance level and this capability has attracted many researchers over the last 50 years. This paper reviews atomic hydrogen investigations and assesses the current state of the art. Future directions for research on this propellant are discussed and trade studies are presented that can be used to establish the "best" engine and space vehicle design conditions.

There has been great progress in the improvement of atom storage density over the last several decades. Laboratory studies have demonstrated 0.2 and 2 mass percent atomic hydrogen in a solid hydrogen matrix. If the atom storage were to reach 10 to 15 percent, which would produce an I_{sp} of 600 to 750 lb_f-s/lb_m, atomic hydrogen might provide an attractive alternative to current chemical propulsion. However, new breakthroughs in production, storage, and transfer technologies are required before atomic hydrogen can be used as a rocket propellant.

Nomenclature

AFPL	U.S. Air Force Phillips Laboratory
ALS	Advanced Launch System
D	Deuterium
DOE	Department of Energy
d_{feed}	Feed Line Diameter (cm)
EPR	Electron-Paramagnetic Resonance
ESR	Electron-Spin Resonance
ETO	Earth To Orbit
H	Atomic Hydrogen
HEDM	High Energy Density Materials
I_{sp}	Specific Impulse (lb_f-s/lb_m)
JPL	Jet Propulsion Laboratory
LLNL	Lawrence Livermore National Laboratory
m_{part}	Particle Mass (kg)
NBS	National Bureau of Standards
NLS	National Launch System
NMR	Nuclear Magnetic Resonance
OAST	Office of Aeronautics and Space Technology
ORNL	Oak Ridge National Laboratory
O_2/H_2	Oxygen / Hydrogen
PPM	Parts Per Million
SSC	Superconducting Supercollider
SSTO	Single Stage to Orbit
T	Tritium

Introduction

Chemical propulsion system studies using metastable propellants or other exotic fuels have been conducted for many years (Refs. 1 to 8), but effective and practical propulsion systems using these fuels have not been demonstrated. The metastable nature of these high energy density materials (HEDM), as well as their unusually short lifetime, has prevented their practical use. However, the understanding of the nature of these potential propellants has

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* Program Manager, Metallized Propellant Program
Member, AIAA

improved significantly over the last several decades (Refs. 9 to 29).

Atomic hydrogen has been of particular interest because its high energy content gives it the potential for high specific impulse. Theoretically, the specific impulse (I_{sp}) can range from 600 to 1500 lb_f-s/lb_m. These I_{sp} values require, respectively, 10- to nearly 100-percent hydrogen atom mass density stored in molecular H_2. This propellant allows up to 82.7-percent reductions in the Gross Lift Off Weight (GLOW) of National Launch System (NLS)-type launch vehicles or increases in payload mass of 14 to 601 percent. Even if only a 15-percent mass density of these atoms are stored in H_2, the result may revolutionize and simplify launch vehicles. The influence of the I_{sp} on the vehicle performance will be discussed later in this paper. Previous work (Ref. 7) has shown that the practical deliverable I_{sp} of atomic hydrogen and the density of the propellant make it applicable only to launch vehicles, a conclusion which is further reinforced by the more-specific findings in this paper.

The first proposals for free-radicals as propellants were presented in 1943 (Refs. 1 and 2). After these initial forays, more-extensive efforts began in the mid 1950's with research sponsored by the National Bureau of Standards (Ref. 3). Research at many international research centers has continued through the present day. The level of understanding of the physics of atomic hydrogen is, however, still painfully low. Applications to rocket propulsion will therefore take many more years of work.

The potential of atomic hydrogen is so great, however, that the interest in it will certainly continue until these atoms are either harnessed or a physical storage limit is reached. A breakthrough in atom storage technology could also improve Earth-storable rocket propellants. Small amounts of added non-cryogenic atoms could increase the I_{sp} of many propellant combinations. Ground-based energy storage of a hydrogen-based economy or one based on other cryogenic fuels for terrestrial applications could also benefit from higher stored energy densities. The applications of atom storage can therefore have many important applications outside of the rocket propulsion community.

This paper describes the current state of the art in atomic hydrogen production and the limits of the atom storage density. Also addressed are feed system options, a set of parametric engine performance predictions, and a brief discussion of the past thruster testing with free radicals is included. A bibliography is also included to cover many additional articles and reports on atomic hydrogen investigations.

Research Summary

Many researchers have conducted significant work in free-radical trapping and storage. The first free radical trapping occurred in 1953-54 (Ref. 9). Nitrogen atoms were deposited in a solid nitrogen matrix and cooled with liquid helium (Ref. 9). The atoms were formed with an electrodeless discharge excited by a microwave voltage, which broke up a small fraction of the molecules of the matrix material. The atoms move to the interstitial spaces of the solid and are stored there. Similarly, oxygen and hydrogen atoms were trapped in a matrix of solid oxygen and hydrogen, respectively (Ref. 9). In 1959, experiments attempting to trap atomic hydrogen achieved a storage density of 6 x 10^{-4} percent (Ref. 3 and 11). The early nitrogen experiments revealed a phosphorescence of the recombining nitrogen. This phosphorescence is prominently noted in much of the future work on free radical hydrogen. The light energy released may be a great fraction of the total energy released from the free radical recombination. This light and its implications for propulsion are discussed later in the paper.

Atomic hydrogen propellant research has advanced significantly in the last half century. A steady increase in the stored atom density in a cryogenic solid matrix has occurred over this period. In Figure 1, the stored atom density is plotted versus calendar year. Both "theoretical" limits and experimental values of atomic hydrogen storage density are depicted. The dates listed in the figure are the source publication dates (see Refs. 1 through 29).

This figure implies that experimental capabilities are improving significantly. Facilities from the Department of Energy (DOE) are now available to conduct very specialized experiments on microscopic samples of atomic hydrogen. As the experiments have improved, modeling and predictions of atom storage have become more sophisticated. The trend of the predicted storage density shows that the "theoretical" limit is improving as the new insights gained from experiments are included.

Figure 1 shows that a new understanding of atomic hydrogen will be needed to make it useful for propulsion. The currently accepted "theoretical" limit for storing free atoms in a solid matrix is 5 percent (Refs. 23 and 24), while the storage density required to make atomic hydrogen attractive is greater than 10 percent. Without improving the storage limit beyond the 5-percent level, atomic hydrogen is not a viable propellant. This will be addressed later in the paper.

Storage Density

The theoretical line shown in Figure 1 is based on the "intuition" and educated guesses of various researchers and not on a rigorous theory. The basis of the line is an assessment of the state of the art at that time, expert opinions, and reasonable extrapolations of the current thinking on the subject. The theoretical storage densities from 1943 to 1980 are maximum amounts based on the work of Windsor (Ref. 3) and Jackson (Refs. 13 and 14). The limit predictions of the late 1950's (Refs. 13 and 14) showed that the maximum density would be a few tenths of a percent. Windsor postulated that the storage density might rise to 1%; earlier, a 10- to 14-percent density was also postulated (Refs. 10 and 12). This higher estimate was based upon the geometrical alignment of a single hydrogen atom with H_2 molecules surrounding it, and reflected only the minimum packing factor for atoms and molecules. It did not address any of the important theoretical or practical subtleties of atom-molecule interactions.

From the 1960's through the 1970's, most of the work that was applicable to propellants was conducted at low cryogenic temperatures between 0.1 and 10 K. Many difficulties with both operations and material physics were encountered when operating at these temperatures. However, the highest storage densities of atomic hydrogen are only possible at the lowest temperatures. The low temperature reduces the mobility of the atoms in the solid lattice. Other methods of storage in a higher temperature gas are possible, but the low density (and consequently very high volume) of the gas makes this method of storing propellant impractical for Earth to Orbit (ETO) launch vehicles.

Much low-temperature atom storage research has been conducted with many differing production methods and measurement techniques. Sharnoff and Pound (Ref. 15) used magnetic resonance to determine the atomic deuterium density. Their experiments showed that the storage density could reach 3×10^{-3} percent (shown in Figure 1). In general, they found that lower temperatures produced the higher storage densities. Data from Ref. 15 show the increase in the number of stored atoms with decreasing temperature.

In Leach's work (Ref. 16), paramagnetic resonance measurements were used to determine the production rate and the lifetime of atomic hydrogen. Though the experimental work was difficult to interpret in some ways, he was able to demonstrate the ability to store H atoms for several hours at a temperature near 4 K.

Hess conducted research looking into the effects of strong magnetic fields on atomic hydrogen storage time (Ref. 17). Though some of his results were inconclusive, he believed that the free-radical storage density could be improved by using intense magnetic fields. Another research program also found that high fields could promote storage of free radicals

(Ref. 18).

Rosen (Refs. 4 and 19) had conducted an extensive set of measurements from 1974 to 1981 (also see bibliography). His work investigated the influence of magnetic fields and attempted to determine some of the limits of atomic hydrogen storage using tritium as a production source of the hydrogen atoms. A total limit of $\approx 7 \times 10^{19}$ atoms/cm^3 (or $\approx 1 \times 10^{-2}$ percent by mass) storage density was predicted with his theory. His experiments were conducted at temperatures as low as 0.1 K and considered the use of triatomic hydrogen molecules to enhance the storage density. His experimental work implied that strong magnetic fields (up to 15 Tesla) did improve the atom storage lifetime. The magnetic field may be able to delay the transition from a spin-polarized state to a ground state and delay the atom recombination.

Current Research

Several directions are being pursued to determine the limits of storage. Parallel research in storing free radicals in solid cryogens is being conducted by NASA, the U.S. Air Force Phillips Laboratory (AFPL, Refs. 8, 23 and 24), and in the former Soviet Union (Ref. 25). The Phillips Laboratory has an extensive program underway in high energy density materials (HEDM) of all types (Ref. 8). Some of their free-radical work has focused on trapping atoms of lithium in solid hydrogen, deuterium, and neon. Laser ablation has been used to produce place lithium atoms in the solid matrix. Research in Russia has continued since 1971 (Ref. 25). Recent Russian research has concentrated on depositing neon and nitrogen in solid matrices and in helium mixtures (Ref. 25). Gaines (Refs. 26 to 28) and Collins (Ref. 29) have conducted the most recent atomic hydrogen experiments. These experiments found the current upper limit of 0.2 to 2 percent atom storage in solid hydrogen. This limit is not, however, considered to be an ultimate limit. The work of Fajardo (Refs. 23 and 24) suggests that the limit may be up to 5 percent molar (of lithium or boron metal atoms in H_2) with current experimental production methods (Ref. 24).

Recent experiments funded by NASA and the AFPL are using the facilities of the DOE. Most of the work is conducted at the Lawrence Livermore National Laboratory (LLNL), where there are many facilities which are geared for measurements of atom recombination that are available from fusion research. In the current LLNL experiments, sapphire microballoons with a mixture of hydrogen, deuterium, and tritium are used to produce atomic hydrogen via tritium decay. These microballoons are 800 to 1000 microns in diameter and are produced by General Atomics in San Diego, CA and EG&G Mound Applied Technologies in Miamisburg, Ohio. The balloons are placed in an Electron Spin Resonance (ESR) machine or photographed with cameras and other sensitive optical instruments at LLNL to determine the energy output from the recombination. Sensitive thermocouples also measure the heat output from the recombining atoms.

Figures 2(a) and 2(b) depict the H atom density in parts per million versus storage time. These measurement were made at LLNL. Figure 2(a) shows the effect of low temperatures on the storage density. At 1.3 K, the density was 7 times that at 5 K. It is clear from this data that very low temperatures are needed for high density storage.

Figure 2(b) illustrates the reduction in atom storage density with the release of a heat spike. Heat spikes, or heat releases, are produced by recombination of hydrogen atoms that have been stored in the solid matrix (Ref. 29). In Figure 2(b), the variation of the number of atoms stored before and after a heat spike is described. The time of the energy release from the recombination event is denoted by the black triangles. Apparently, the solid matrix is able to hold a specific amount of energy and then can do no more to prevent atom recombination. After the heat release occurs, the atom level drops precipitously. During a period of approximately 1000 to 7000 minutes, as shown in Figure 2(b), the number of atoms once again builds back to a high level because of the constant beta decay source from the tritium. Once the storage density reaches approximately 600 PPM, recombination occurs again and the density of stored atoms drops again.

Experiments have shown that the energy from atom recombination is released in both heat and light. Optical instruments are used to determine the energy release mechanism. Light emission from the recombination was scrutinized in the ultraviolet, visible, and infrared at LLNL (Ref. 22). Figure 3 shows the relative intensity of light energy released from H recombination versus wavelength. The emission spectrum ranges from 480 to 900 nanometers. A major energy peak is centered near 800 nanometers in the near infrared. There is currently no clear understanding of the energy peak's implications.

Several techniques have been used to determine atom storage density and the resulting energy storage ability of the H/H_2 matrix. Measurements of the number of electron spins, or the number of unpaired atoms, are made with ESR. There is a factor of nine to ten discrepancy with ESR measurements and the Nuclear Magnetic Resonance (NMR) measurements (Refs. 26 to 29). The ESR predicts that there will be a stored density of 0.1 to 0.2 percent H in H_2. The energy measured with NMR (Ref. 46), however, implies that the stored mass of H is nine times that of the ESR measurements. This 90 percent discrepancy in the total amount of the energy is being investigated in several ways. One of these possibilities is that all of the missing or discrepant energy is released as light. The continuing research has not yet reconciled the different theories of where the energy is stored and how it is released.

These studies have very profound implications for the use of atomic hydrogen in launch vehicle propulsion. If a large amount of energy emanates from the atom recombination as light, it may frustrate any propulsion application. The thermal energy of combustion (or, in this case, atom recombination) is typically what heats the propellant and drives a rocket engine. If the energy cannot be extracted thermally, or in some other controlled manner, atomic hydrogen may not be a viable rocket propellant.

Atom recombination, with the consequent production of the heat spikes and optical flashes, occurs very quickly. The reaction might be likened to an uncontrolled chemical explosion. If this recombination can be controlled, as we have certainly controlled the combustion in a rocket engine, the result may be an extremely high performance chemical propulsion system.

Thoughts for the Future: Atomic Hydrogen Propellants

The preceding discussion reviewed research results for very-small-scale production and storage of atomic hydrogen. To be practical for rocket propulsion, the production rate and storage capacity must improve dramatically. Modern experiments use nanogram samples of atomic hydrogen, whereas up to many hundreds of tons may be required for each launch from Earth to orbit (Ref. 7). The propellant's practicality is based on achieving the required storage density, reliable storage, and propellant transfer, and delivering the needed engine performance. Each of these issues is discussed in this section.

Production

Three methods of producing atomic hydrogen have been considered in the past. They are tritium decay (Ref. 26), electron or other high-energy beams (Ref. 16), and radiofrequency or other glow discharge excitation (Ref. 17). Tritium decay has been the method of choice for most of the most-recent experiments with atomic hydrogen (Ref. 26). This is because of the existing facilities that readily produce it for the DOE fusion program (Ref. 30). The tritium decay process, reviewed in Ref. 30, is very complex, with many different nuclear particles being produced. Tritium radiation from beta particle decay is a constant energy source term. The decay process also damages the surrounding matrix, further limiting the capability of the solid to store the atoms. This energy must be controlled and "shut off" to allow the atomic hydrogen to lie stably in its solid matrix.

Since tritium's beta production cannot be turned off, an alternate method of production is required. The production directions for atomic hydrogen will move away from the use of tritium and employ high energy beams or radiofrequency excitation. Electron beams or other high-energy beams would deposit energy into the molecular hydrogen, break them up into atoms and make free radicals. Another method, using radiofrequency excitation or microwaves, allows the atoms to be formed with a fairly minimal disturbance.

Other innovative methods of atomic hydrogen production may include nanotechnology and microlasers (Refs. 31 to 36). Nanotechnology has already been applied to single-atom manipulation (Ref. 31). Figure 4 illustrates the relative size of a nanotechnology factory on a microchip (Ref. 32). Nanometer-sized machines might be used to lay down layers of propellant matrix, building up the propellant elements that would comprise the entire load for a rocket stage. Microlasers might also be used in producing atomic hydrogen (Refs. 34 to 36). These microscopic lasers are fabricated on a silicon wafer and might be used to deposit small bundles of energy onto a hydrogen plate, creating the stored atoms. Formation of the atomic hydrogen fuel would have to be closely linked, physically, to the energy output of the laser. This proximity may create unacceptable thermal isolation problems and undesirable disturbances of the atoms.

Storage and Handling

Long term storage of atomic hydrogen is required if it to be used for practical space transportation. Long term storage of atomic hydrogen can be expressed in terms of weeks or months. Certainly, the dynamic nature of this free radical will make extremely long-term storage of months or years infeasible or operationally undesirable.

A launch facility for atomic hydrogen-powered vehicles might include high field, superconducting magnets. A general configuration for these magnets is given in Figure 5 (Ref. 37). They were designed for a proposed version of the Superconducting Supercollider and a similar configuration might be used for a launch system. The vehicle would be surrounded by these magnets during fueling. In fact, the magnets could be an integral part of the ground storage and launch support system. Conceptually, the propellant tankage could also be the ground storage tank. The vehicle would then be assembled around the building blocks of the tankage. Prior to launch, the magnets and their support structure would be removed and the vehicle would be free to lift off. The mass of the magnets, which depends on the magnetic field strength, could make their structure very massive. Thus, it appears that atomic hydrogen may be practical for only ETO vehicles and upper stages would be severely penalized by the magnet mass. This further supports the previous conclusion that ETO propulsion is the most likely candidate for atomic hydrogen. Additional experimentation should be able to more accurately quantify the influence of the magnetic field on the storability of atomic hydrogen and the magnet's influence on launch operations.

Feed System

To produce the highest possible engine I_{sp}, the molecular weight of the exhaust should be as low as possible and the recombination temperature should be very high. The matrix in which the atoms are stored is therefore chosen to provide the lowest practical molecular weight. Because hydrogen has the lowest molecular weight, choosing hydrogen for the solid in the matrix will deliver the highest rocket performance. However, hydrogen currently has certain inherent storage density limitations. It does, however, remain the most likely matrix candidate. The propellant feed system must provide a flow of a solid cryogenic H/H_2 matrix from a propellant storage tank to the rocket engine.

Transporting the propellant from the tank to the rocket engine will be a major challenge. Past studies (Ref. 6) have investigated the storage of the atomic hydrogen matrix as solid rods that are insulated from one another. Each rod is consumed to produce thrust. There are several disadvantages to this method: heat flow to the other fuel elements, the very short lifetime of the insulators in this thermal environment, and the relatively unbridled fuel flow and thrust created by the rapidly-recombining fuel. In these previous designs, the rods had a relatively thin insulator between the fuel rods (Ref. 6). Because the fuel recombines so quickly, there may a very steep temperature gradient near the fuel. The heat generated is very intense and it is difficult to insulate the remaining propellant rods from the high temperatures. Thermally isolating the fuel rods is possible, of course, but the mass and volume of the required insulation would be very high. The Jet Propulsion Laboratory (JPL) is continuing some of these feed system studies with the AFPL (Refs. 38 and 39).

Small pellets are a likely avenue for transporting the atomic hydrogen propellant (Ref. 40 and 41). Such pellets are used extensively in cryogenic fuel injection for hydrogen-deuterium-tritium fusion reactors. A two-phase flow system, in which a carrier fluid transports the propellant pellets to the rocket engine, may be required. A stream of liquid helium could be used as a carrier fluid for the pellets (Refs. 6, 38, and 39). The helium has a higher molecular weight than H_2 and therefore will reduce the I_{sp}. To obtain the maximal performance, the helium should be removed from the propellant flow and recirculated prior to entering the engine. However, the method of stripping the helium from the flow prior to injection into the recombination chamber is not clear. Another fluid may be chosen that more-nearly matches the fluid properties of the solid atomic hydrogen and hydrogen particles. Liquid hydrogen with some dopant or additive to lower its freezing point is a possibility.

If the helium carrier fluid were not removed, the performance of the engine would be reduced because the molecular weight of helium is higher than hydrogen. However, the overall propellant density would increase due to the higher density of liquid helium over solid hydrogen. A preliminary performance assessment shows that the density of the overall propellant increases to 111.2 from 88.0 kg/m^3 and the engine I_{sp} is reduced to 1132 from 1200 lb$_f$-s/lb$_m$. This analysis uses the H/H_2 loading of 61.5 percent and a helium-H/H_2 volume ratio of 1:1. This volume ratio corresponds to a 1.421 mixture ratio. For the engine analysis, the expansion ratio was 50:1 and the chamber pressure was 1000 psia. Further analysis on the overall vehicle performance and the masses of the helium-hydrogen feed system are required to determine the full effect of the helium addition over a range of design conditions.

Another feed system consideration is the physical size of the feed lines. Figure 6 shows the line diameter and atomic hydrogen particle flow rate versus the particle mass. This analysis allows the determination of acceptable line sizes for a feed system. In the figure, the mass flow rate of H/H_2 particles is 1340 kg/s and the particles are suspended in a helium carrier fluid. This mass flow rate is needed for the first stage of an NLS (I_{sp} = 750 lb$_f$-s/lb$_m$, Ref. 7).Using the figure, a parametric estimate of the particle sizes and the associated line sizes needed to support this flow rate is made. In sizing the lines, a cylindrical H/H_2 particle was used. Its length to diameter ratio (L/D) was 1:1 and its density was 88.0 kg/m^3. To carry the particle, a solid to liquid volume fraction of 50 percent was used, based upon the flow experience with slush hydrogen (Ref. 42). The size of the feed line was calculated using:

$$d_{feed} = (m_{part} * 8000/ [\pi * 0.088])^{1/3} \text{ (cm)}$$

where d_{feed} is the feed line diameter in cm and m_{part} is the particle mass in kg.

For a particle size of 148 kg, the line diameter is 162 cm. To support the 1340-kg/s flow rate needed, approximately nine of these particles must enter the recombination chamber per second. This design seems impractical and it therefore appears that the larger pellet sizes will not be suitable for atomic hydrogen vehicles.

Smaller, millimeter-sized pellets would potentially allow easier storage and delivery to the recombination chamber.

Other options are to use the propellant in a semi-monolithic mass similar to a solid rocket motor (Ref. 6). Figure 7 describes H propellant stored with layers of insulators between the propellant elements. Rather than having the insulators parallel to the flow field (Ref. 6), they would be perpendicular as shown in Figure 7. This idea is similar to solid rocket motor throttling concepts considered in the past (Ref. 43). The only propellant that would be consumed would be that needed for the individual impulses. A pulsatile thrust might be feasible for large throat engines and high length-to-diameter (L/D) vehicles. The high L/D may ease some of the problems of propellant feed by minimizing turns and other necessary obstructions in the feed system. Propellant in this high L/D case might be laid down in thin layers to improve the production and storability of the free radicals. This of course would also lend itself to segregating the propellant elements.

Engine Performance

Engine performance simulations were conducted using a one-dimensional rocket performance code (Ref. 44). These simulations include both equilibrium flows and the losses due to a frozen flow assumption. Wall recombination losses, which are discussed below, were not included. Two chamber pressures and a wide range of atomic hydrogen loadings have been analyzed. Figures 8 and 9 depict the engine I_{sp} versus H loading in H_2 for 30- and 1000-psia chamber pressures. The H loading in H_2 ranges from 0 to 100 percent. An expansion ratio of 50:1 was selected for the launch vehicle design. The engine design parameters for two cases are presented in Table I.

The figures show that the equilibrium and the frozen flow performance are similar for H loadings below 20 percent. Above this level, the frozen flow assumption is very important to consider because significant errors in the performance prediction can occur at high H loadings.

Another potentially serious issue is the ability to contain rocket chamber and nozzle flows of atomic hydrogen. Based on initial testing conducted at NASA Lewis and Michigan State University (Refs. 5, 45 and 47), during a firing of helium and nitrogen free-radicals in a thruster test, the engine walls would absorb a large fraction of the atoms if the engine pressure were very low: several torr. This migration to the walls occurred because the collisional frequency is low at low pressure. Recombination at higher pressures (one or several atmospheres) would alleviate this problem. The testing was conducted with a microwave plasma thruster (Refs. 47 and 48). The higher pressure allowed the plasma and the recombination zone to be restricted to a region in the chamber and a relatively cool thin boundary layer separated the plasma from the walls (Ref. 47).

Table I
Atomic Hydrogen Engine Performance Parameters

H Loading (%)	15.4	61.5
I_{sp} (lb_f-s/lb_m)*	750	1200
Chamber Pressure (psi)	1000	1000
Expansion Ratio	50	50
Molecular Weight, exit	2.016	1.621
Chamber Temperature (K)	2189	4639
C_f (e = 50:1)	1.711	1.699

* I_{sp} efficiency = 0.9387

In Ref. 7, preliminary engine performance estimates were provided based on simple ideal gas assumptions. Higher fidelity I_{sp} values, including frozen flow effects, are presented in this paper. At atomic hydrogen loadings above 20 percent, the effects of frozen flow seriously degrade the engine performance. Past predictions have not taken the frozen flow assumption into consideration and have predicted an atomic hydrogen engine I_{sp} of up to 2150 lb_f-s/lb_m (Refs. 4 and 6). Including these frozen flow losses, a more reasonable upper limit of 1500 lb_f-s/lb_m is obtained. This limit, however, will be difficult or impractical to attain; a fuel composed of 100-percent atomic hydrogen would be needed. Currently, it is difficult to conceive of storing atomic hydrogen, that is useful for rocket propulsion, without some sort of matrix. The I_{sp} value of 750 lb_f-s/lb_m appears to be a more attainable goal, only requiring an H storage density of 15 percent.

Figure 10 describes the influence of the engine I_{sp} on GLOW. The data for the NLS and the atomic hydrogen vehicle design are provided in Reference 7. Based on the improved engine simulations, the GLOW of a 600-lb_f-s/lb_m and a 1200-lb_f-s/lb_m vehicle was estimated. These I_{sp} values correspond to 10 percent and 61.5 percent H in H_2, respectively. The 600-lb_f-s/lb_m engine was able to reduce the GLOW by 10.3 percent, whereas the 1200-lb_f-s/lb_m vehicle enabled a 78 percent GLOW reduction. The 1200-lb_f-s/lb_m performance level is able to nearly achieve the 82.7-percent GLOW reduction that is possible with a 1500-lb_f-s/lb_m I_{sp}. Even with only an I_{sp} of 750-lb_f-s/lb_m, a reduction in GLOW of 51.7 percent is possible.

Atom loadings below 10 percent were not attractive for propulsion. At a 5 percent level, the I_{sp} produced was comparable to the 430-lb_f-s/lb_m NLS O_2/H_2 engines. With all of the added complexity and relatively-high dry weight for the storage of atomic hydrogen, the overall vehicle performance would be poorer than using traditional O_2/H_2 propulsion.

An alternative method of improving the launch system is to fly a higher payload mass per flight. In this analysis, the GLOW is a constant value of 1,891,500 kg and the baseline payload is 96,000 kg. A payload increase of 14 percent is enabled with the 600-lb_f-s/lb_m performance level and with 750 lb_f-s/lb_m, the payload increase is 131 percent.

Concluding Remarks

Atomic hydrogen propellant may provide a large increase in vehicle performance over conventional chemically-based systems. This performance increase is, however, dependent upon significant increases in storage density of hydrogen atoms in a solid hydrogen storage matrix. Currently, only a 1- to 2-percent storage density is achievable with atomic hydrogen. A 15 percent level will make the propellant very attractive for Earth-to-Orbit propulsion if solutions to the severe storage and feed system difficulties are found.

Currently, the theoretical atomic hydrogen storage limit is 5 percent. This low value is inadequate to deliver any payload performance advantage versus O_2/H_2-powered vehicles. A 10-percent level will deliver an I_{sp} of 600 lb_f-s/lb_m, and allow a significant payload increase of 14 percent, but at a 15.4 percent, the I_{sp} produced is 750 lb_f-s/lb_m and enables a 131-percent payload increase or a 51.7-percent GLOW reduction. Though higher atomic hydrogen storage densities will theoretically produce a higher I_{sp}, it may be impractical to store hydrogen atoms at a density any higher than 15 to 20 percent. Future work should focus on delivering at least this level of stored atoms.

Production and storage research has shown a trend toward higher densities over the last several decades and the predicted density is becoming more-closely aligned with the experimental data. It is not clear, however, that the trend will continue to improve or whether we have reached a true limit of atom storage. Improved techniques in atom storage are being investigated. Only by continuing to pursue these techniques can we hope to answer the questions about the ultimate limit of atom storage density.

Currently, the energy emitted from the recombination of atomic hydrogen is both optical (ultraviolet, visible and infrared light) and thermal. There is approximately 10 times more energy measured using NMR than using

ESR. It is also not clear how much of the energy is released as light and how much as heat. This distribution of the energy release is not fully understood and could be a major barrier to using atomic hydrogen as a rocket propellant.

Producing large quantities of atomic hydrogen is another major stumbling block. Current methods of production for research samples make about one nanogram of atoms. For an NLS-type vehicle, delivering 96 tons to LEO, over 441 tons of propellant is needed for the first stage and 153 tons for the second stage. There are many questions that would need to be answered before such large facilities for producing many hundreds of tons of atomic hydrogen would be practical.

Improving the storage life of hydrogen atoms may be possible with very high field magnets of tens of Tesla. These magnets will be very massive and they must be an integral of the production and launch facility. Combining the production tank, with its associated magnets, and the actual launch vehicle stages may be one way of minimizing the losses due to recombination during production and later transport of the propellants.

Recombination of hydrogen atoms occurs very quickly and there is little control of this reaction unless the atoms are extremely cold: 2 to 4 K. Maintaining this temperature while transporting the propellant through an operational propulsion system will not be easy. During the operation of the engine, large flows of cryogenic particles will be needed without there being any recombination of the atoms within or between those particles. The aspects of feed systems and engine performance are, therefore, serious design challenges. Feeding propellant elements to the recombination chamber will be very difficult unless a creative solution to handling those particles can be developed.

Engine performance is heavily dependent upon the stored atom density. At a storage level above 15.4 percent, the I_{sp} of the atomic hydrogen engine can be greater than 750 lb_f-s/lb_m and produce either very large reductions in launch vehicle GLOW or large increases in the payload delivered to LEO. Great savings are possible at 1200 and 1500 lb_f-s/lb_m: up to 78 and 82.7 percent GLOW reduction, respectively.

There are now difficulties in stably storing atomic hydrogen, feeding it to a rocket engine and producing highly efficient engine performance. The potential, however, is great. Investments in free-radical propulsion may also pay off in other lower I_{sp} applications. Thus even if the full potential of atomic hydrogen is not realized, there may be an extremely useful product in ground-based energy storage, propulsion or other related technologies.

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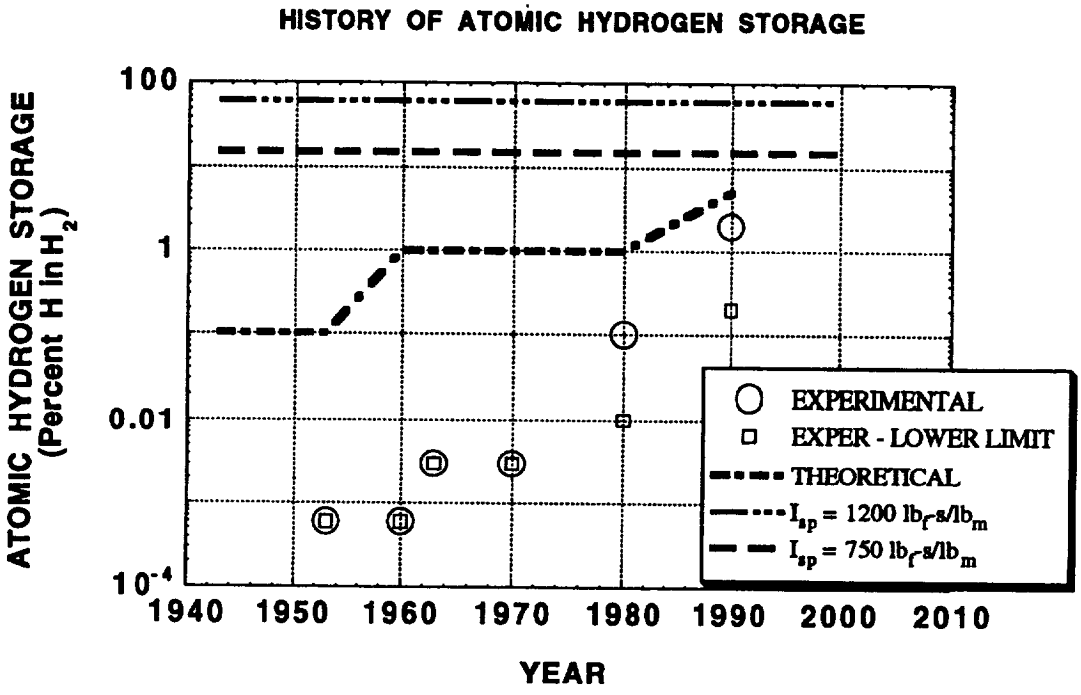
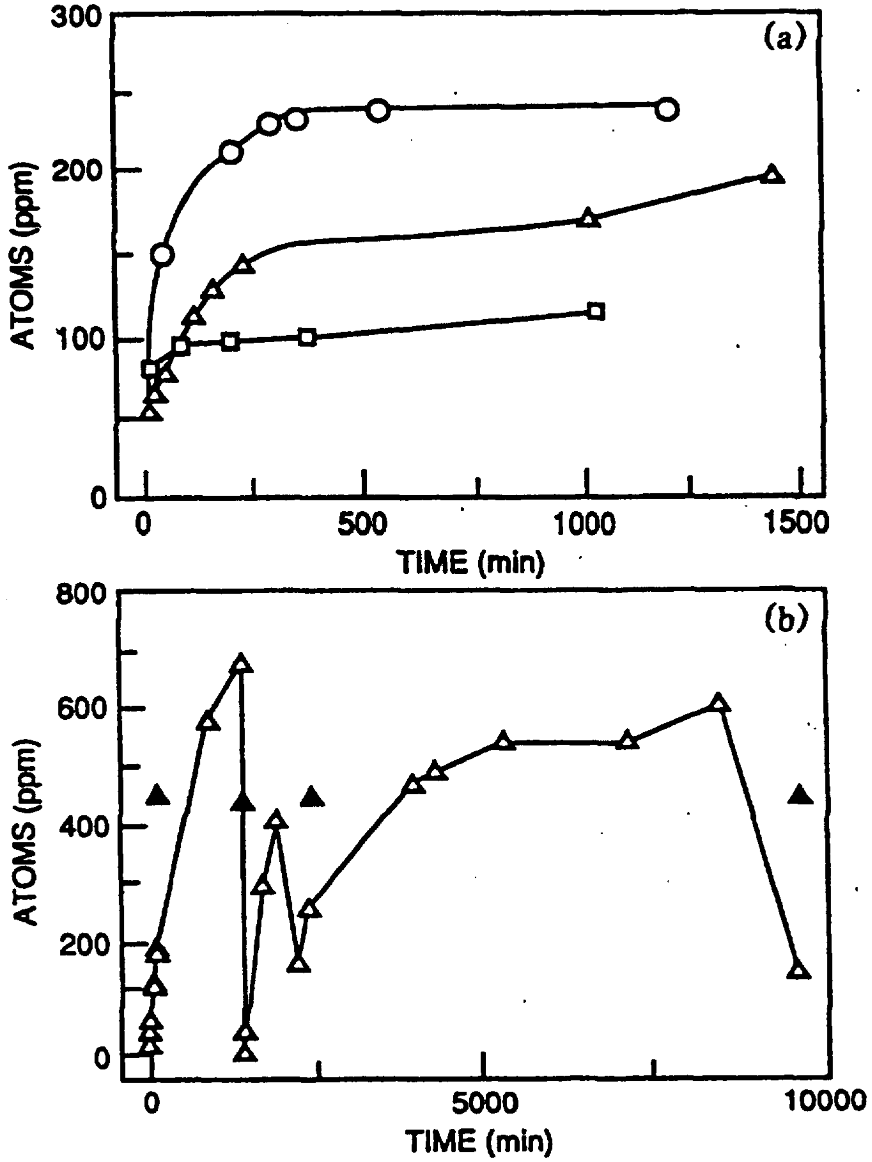


Figure 1. History of Atomic Hydrogen Storage Density



(a) ESR measurements of the T-atom concentration (in parts per 10^6) in D-T at three different temperatures: (□) 5.1, (△) 4.1, and (○) 3.1 K. (b) The effect of thermal spikes (▲) on the total D-atom concentration (△) as seen by ESR in solid D_2 containing 2% tritium held at 1.3 K. These spikes were not intentionally triggered.

Figure 2. Atomic Hydrogen Storage Density vs. Time (Ref. 29)

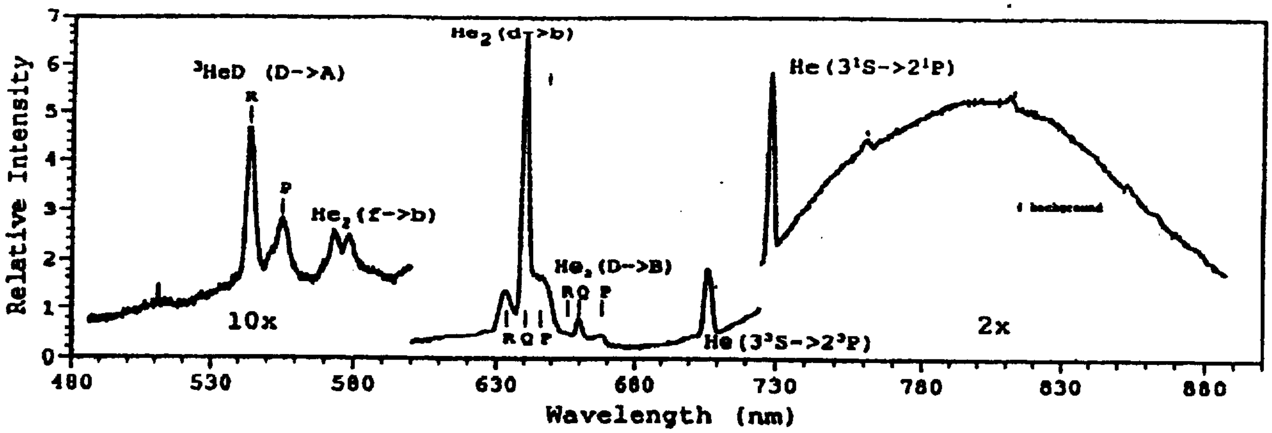


Figure 3. Atomic Hydrogen Recombination Spectrum - 800 nm Peak Energy (Ref. 22)

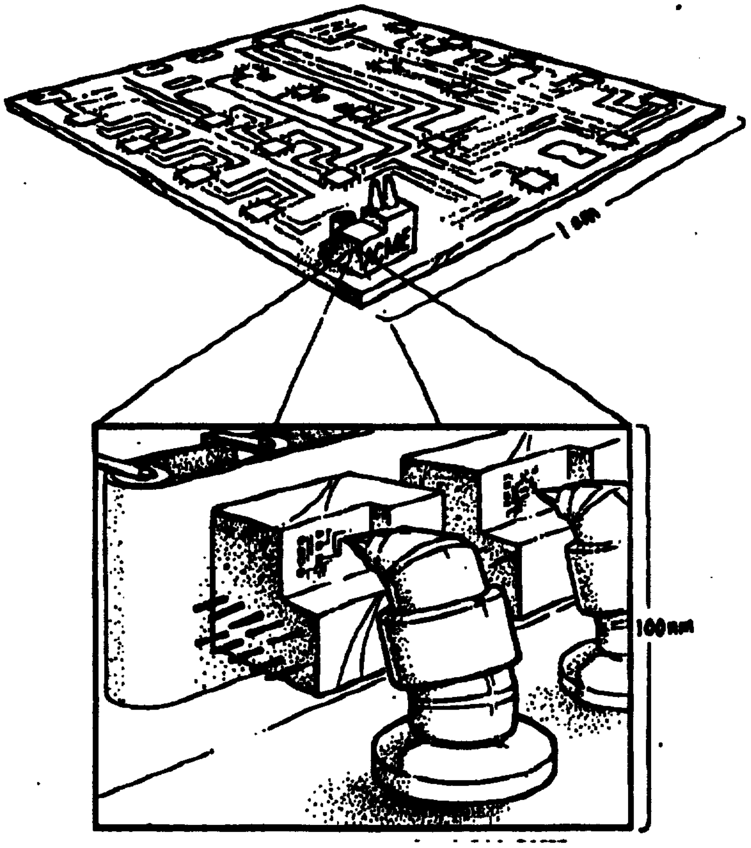


Figure 4. Nanotechnology Example - Microchip-Sized Factory (Ref. 32)

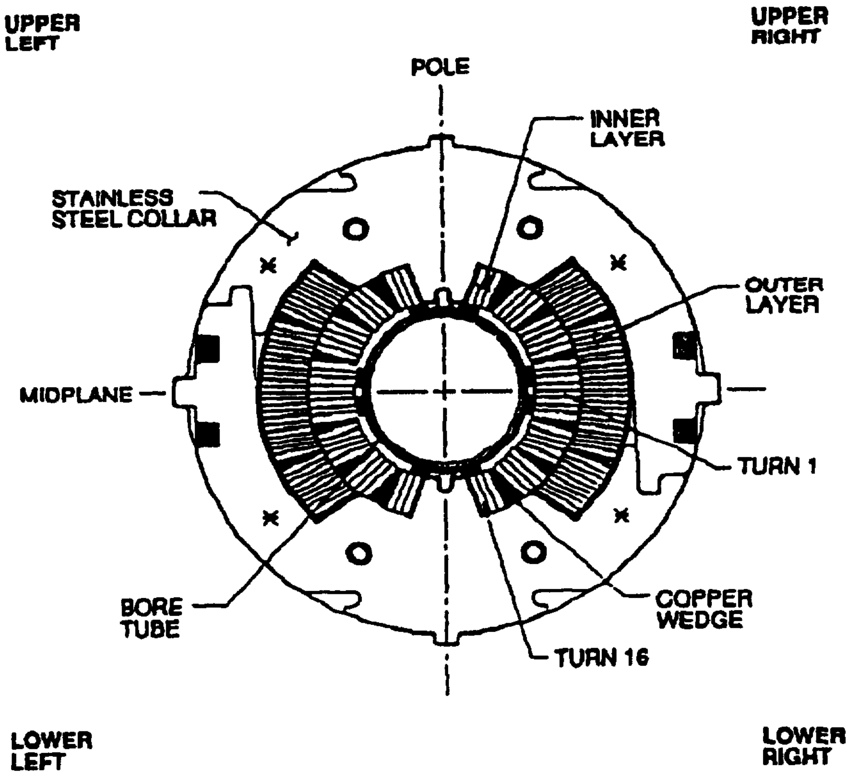


Figure 5. High Field Magnet Configuration (Ref. 37)

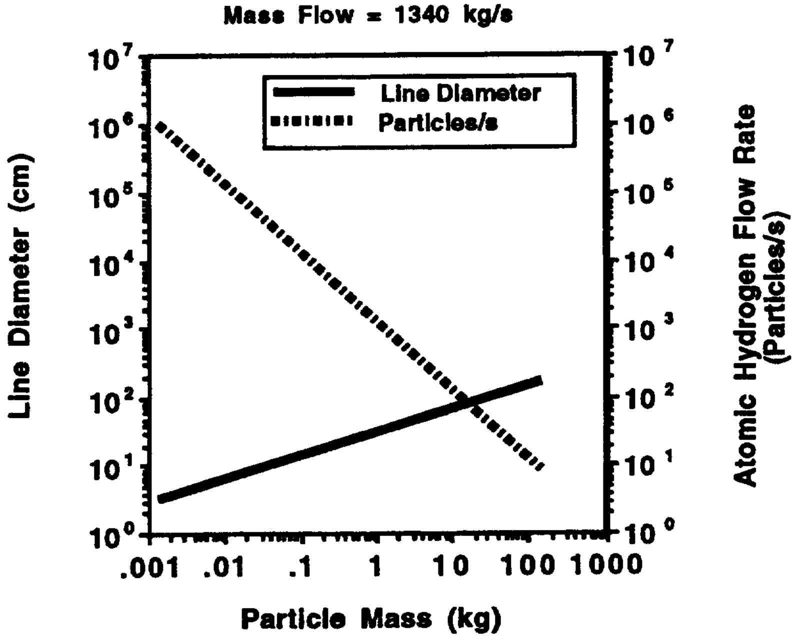


Figure 6. Atomic Hydrogen Particle Feed System Sizing

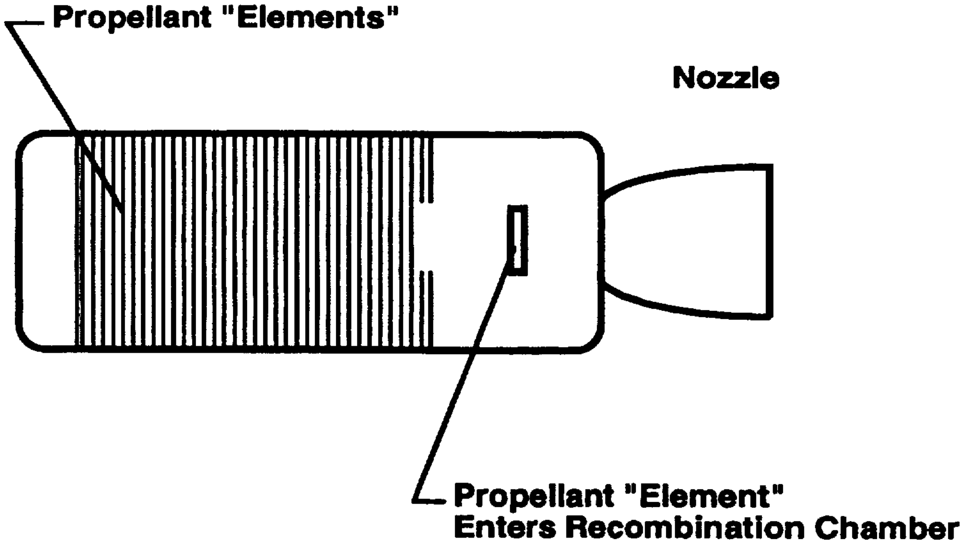


Figure 7. Atomic Hydrogen Propellant Elements: Conceptual Configuration

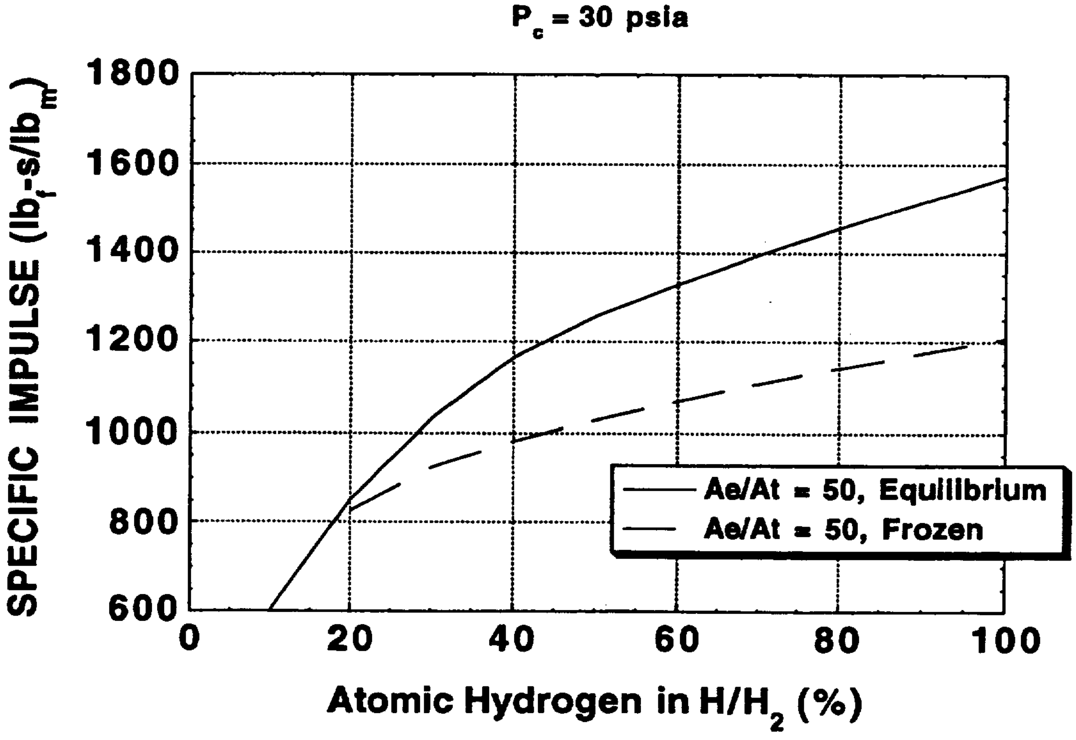


Figure 8. Atomic Hydrogen Engine Performance: P_c = 30 psia

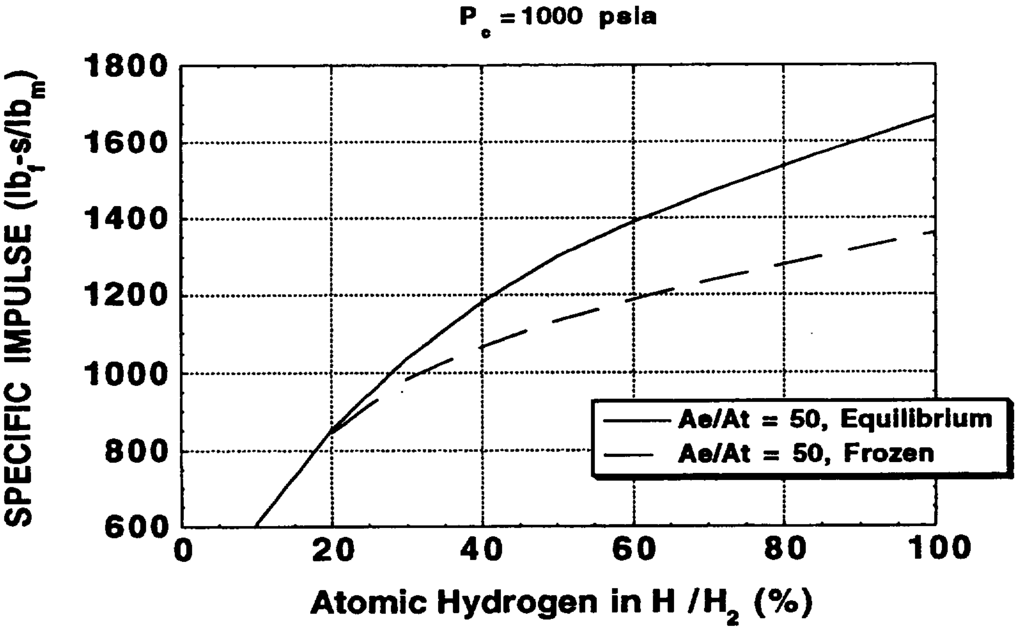


Figure 3. Atomic Hydrogen Engine Performance: $P_C = 1000$ psia

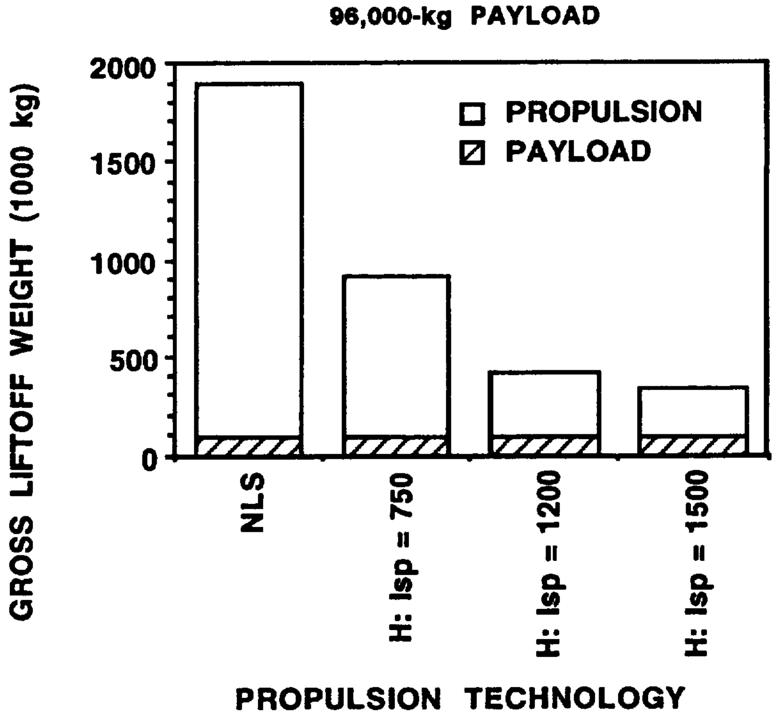


Figure 10. Launch Vehicle GLOW for 96,000 kg Payload: NLS and Atomic Hydrogen

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

Very high energy density, free-radical propellants such as atomic hydrogen may enable unique launch vehicle propulsion applications. Atomic hydrogen could deliver a specific impulse between 600 and 1500 lb_f-s/lb_m performance level and this capability has attracted many researchers over the last 50 years. This paper reviews atomic hydrogen investigations and assesses the current state of the art. Future directions for research on this propellent are discussed and trade studies are presented that can be used to establish the "best" engine and space vehicle design conditions. There has been great progress in the improvement of atom storage density over the last several decades. Laboratory studies have demonstrated 0.2 and 2 mass percent atomic hydrogen in a solid hydrogen matrix. If the atom storage were to reach 10 to 15 percent, which would produce an I_{sp} of 600 to 750 lb_f-s/lb_m, atomic hydrogen might produce an attractive alternative to current chemical propulsion. However, new breakthroughs in production, storage, and transfer technologies are required before atomic hydrogen can be used as a rocket propellent.

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