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Technology Issues Associated With Using Densified Hydrogen for Space Vehicles

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TECHNOLOGY ISSUES ASSOCIATED WITH USING DENSIFIED HYDROGEN FOR SPACE VEHICLES

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Abstract

Slush hydrogen and triple-point hydrogen offer the potential for reducing the size and weight of future space vehicles because these fluids have greater densities than normal-boiling-point liquid hydrogen. In addition, these fluids have greater heat capacities, which make them attractive fuels for such applications as the National Aero-Space Plane and cryogenic depots. Some of the benefits of using slush hydrogen and triple-point hydrogen for space missions are quantified in this report. This report also examines some of the major issues associated with using these densified cryogenic fuels for space applications and summarizes the technology efforts that have been made to address many of these issues.

Introduction

Because of its high energy content and its relatively large cooling capability, hydrogen has been the fuel of choice for existing space vehicles such as the space shuttles. These same reasons led to the selection of hydrogen to fuel the National Aero-Space Plane (NASP), a horizontal takeoff and landing vehicle to be built in the late 1990's. Hydrogen has the disadvantage, however, of having low density, thus requiring large fuel tanks. Slush hydrogen (SLH_2), a mixture of solid and liquid hydrogen, offers the advantages of higher density (15 percent at 50-percent solid fraction) and higher heat capacity (18 percent) than normal-boiling-point liquid hydrogen ($NBPH_2$). These increases in density and heat capacity provide a potential decrease in the gross vehicle weight. For this reason, SLH_2 has been selected as the baseline fuel for the NASP vehicle.[1] Triple-point hydrogen (TPH_2), liquid hydrogen at 1.02 psia and 24.8 °R, also offers increases in density (8 percent) and heat capacity (12 percent) in comparison to $NBPH_2$. Although these benefits are not as large as those for SLH_2, TPH_2 does not have the added complication of solid particles, and thus may also be an option for future space vehicles.

Several small-scale experimental efforts were conducted in the 1960's and 1970's to investigate various aspects of SLH_2 production and flow.[2-4] The advantages of using SLH_2 in space vehicles were recognized at this time, and analytical studies were performed on the use of the fluid for the space shuttles.[5] No known experimental investigations were conducted with TPH_2 during this time period. More recently, an experimental and analytical modeling effort under the NASP program at the NASA Lewis Research Center[6-8] examined the operational aspects of both SLH_2 and TPH_2. In addition, efforts were also made at the McDonnell-Douglas Space Systems Company and the National Institute of Standards and Technology (NIST) to provide data on the feasibility of using SLH_2 for the NASP.[9-11] These experimental and analytical studies were performed to develop a fundamental understanding of and to generate design information on the use of densified hydrogen for the NASP. The information gained from the NASP program may be applicable to other space vehicles.

The potential benefits of using densified hydrogen have been quantified[12] and are presented in this report for Earth-to-orbit transportation vehicles (space shuttle (STS) and space shuttle cargo (STS-C)), space exploration mission transfer vehicles (lunar outpost missions), and cryogenic depots in low-Earth orbit. However, prior to the use of SLH_2 or TPH_2 on the NASP or other space missions, some technology issues must be resolved. As discussed in a previous report,[13] technology issues investigated by the NASP program have included aspects of production, ground operations, flight operations, and safety. This report represents a follow-on to Ref. 13, re-examining issues associated with using SLH_2 or TPH_2 for space vehicles and discussing the experimental and analytical efforts that were performed under the NASP program to resolve some of these issues. In addition, recommendations for future work on SLH_2 or TPH_2 are made in regards to their use for future space missions.

Benefits of Slush Hydrogen

National Aero-Space Plane

Although liquid hydrogen is a high-energy propellent, it has a low density; hence, large fuel tanks would be required if it were chosen as the NASP fuel. A primary goal for the NASP, or X-30, vehicle is to achieve single stage to orbit. Tradeoff studies show the required propellant fraction as a function of takeoff gross weight to achieve single stage to orbit.[14] If the vehicle design shows that the propellant fraction available is less than the required propellant fraction, then "closure" is not achieved, and the vehicle design is not successful. Therefore, the volume of the fuel tanks is critical to reducing structural weight and providing enough fuel to meet the mission requirements, especially in an experimental vehicle such as the NASP, which has little design margin. Densifying the hydrogen fuel reduces the volume and makes possible the achievement of successful NASP vehicle designs that provide the single-stage-to-orbit capability. As discussed earlier, the density increase for TPH_2 is 8 percent, and the increase for SLH_2 is 15 percent.

In addition to providing a density increase, TPH_2 and SLH_2 offer an increase in cooling capability. Because the NASP will operate at hypersonic speeds to achieve orbit, high heat loads may be imposed on the vehicle. Therefore, active cooling may be required on large areas of the NASP. With the use of densified propellants with their increased cooling capability (approximately 12-percent increase for TPH_2, 18-percent increase for 50 percent SLH_2), more heat can be absorbed during flight and less propellant boiloff may occur, further reducing the overall weight of the NASP by reducing propellant losses. One option being considered for NASP is the use of a recirculation process, where some of the vaporized fluid used for cooling is recondensed in the main propellant tank. The additional cooling capability of the densified hydrogen may allow more gaseous hydrogen to be condensed, thus less fuel would be required for takeoff. According to Ref. 9, the size of the vehicle may be reduced by up to 30 percent with SLH_2. The increased density and cooling capability of TPH_2 or SLH_2 may significantly reduce the size and the weight of the NASP.

Space Missions

In a report summarizing a study performed for NASA Lewis by Science Applications International Corporation,[12] the benefits of using SLH_2 for space missions were examined. Applications of SLH_2 considered in the study included Earth-to-orbit transportation vehicles (STS and STS-C), exploration mission transfer vehicles (such as a lunar outpost mission), and cryogenic depots in low-Earth orbit. The benefits were expressed in terms of initial mass differences at constant payload, payload differences at constant propellant tank volume, and changes in fuel storage time for space-based cryogenic depots.

Figure 1 shows the results of the study for the STS and STS-C. From Fig. 1(a) it can be seen that, assuming no redesign of the existing space shuttles, TPH_2 offers the potential for a 2000-lb_m payload gain, or a 5-percent increase in payload. The payload increase assumes an improvement due to the density increase (hydrogen load) and due to a specific impulse increase. This specific impulse increase results from a change in the fuel-to-oxidizer mixture ratio when more hydrogen is loaded into the External Tank. SLH_2 offers a potential increase in payload of 3670 lb_m, or a 9-percent increase in payload, when both the hydrogen load and the specific impulse effects are considered. In Fig. 1(b), for the STS-C, the gains in payload are similar to those for the STS. TPH_2 has the potential for a 2000-lb_m increase in payload, whereas SLH_2 offers the potential for a 3700-lb_m increase. The percentage increase in payload is lower with the STS-C mission in comparison to the STS mission because the base payload is much higher for the STS-C. Note that no additional equipment was included in the analysis. The weight of this equipment, which may be required for a SLH_2 system, may reduce the benefits shown here. Also, practical operational considerations, such as shuttle hydrogen residuals and structural limits, should be included in future studies.

Figure 2 shows the benefits of densified hydrogen for a lunar outpost mission. In this mission, three propulsion schemes were used: a cryogenic oxygen/hydrogen lunar transfer vehicle with an aerobrake, a nuclear thermal propulsion system with an aerobrake return, and a nuclear thermal propulsion system with a propulsive return. The initial mass in low-Earth orbit is shown in Fig. 2(a) for each propulsion option. Figure 2(b) shows the initial mass savings at constant payload. The mass reductions ranged from 1.5 percent for the cryogenic oxygen/hydrogen lunar transfer vehicle with an aerobrake to 6 percent for the nuclear thermal propulsion system with propulsive return, with little difference seen in the TPH_2 and SLH_2 cases. The improvement was largest for the nuclear thermal propulsion system because all the propellant was hydrogen. Figure 2(c) shows the percentage increase in payload at constant tank volume. The corresponding increases in initial mass associated with these payload gains are presented in Fig. 2(d). The payload increases ranged from 4 to 19 percent for the TPH_2 cases and from 5 to 29 percent for the SLH_2 cases. The absolute payload gains for densified hydrogen ranged from 2 metric tons to 13 metric tons for the cases considered.

Figure 3 shows the boiloff as a function of storage time for a cryogenic depot that contains 100 metric tons of hydrogen and 600 metric tons of oxygen. This system assumed a 5-percent ullage volume and a standard multilayer insulation on the tanks. By using TPH_2, approximately 3 months of additional storage time is provided to reach 90 percent of the initial tank loading; for SLH_2, approximately 5 months of additional storage time is gained. This increase in storage time is attributed to the increased heat capacity with TPH_2 and SLH_2. With SLH_2, both the sensible heat (the heat required to raise the liquid temperature from triple point to normal boiling point) and the latent heat of fusion must be absorbed before vaporization begins. With TPH_2, the sensible heat is available to prevent boiloff. Therefore, densified hydrogen fuels offer potentially significant benefits for a variety of space missions.

Technology Issues

Production

The production of densified hydrogen does not appear to be a difficult task. Several production methods for SLH_2 have been demonstrated at the laboratory level, and densifying hydrogen to a triple-point liquid is easily achieved by pumping to reduce the fluid to triple-point pressure and temperature. The SLH_2 production methods include evaporatve cooling processes, such as the freeze-thaw[3,15] and the spray technique,[15] and refrigeration processes, such as auger[16] and magnetic refrigeration.[17] The major issues related to production of SLH_2 include large-scale production, methods of production, safety concerns, and energy efficiency and costs associated with a large-scale production plant.

The large-scale production of SLH_2 is seen as a manageable engineering problem. The freeze-thaw method is the most characterized of the production methods and was selected to conduct larger scale SLH_2 production studies under the NASP program. The first large-scale production challenge was to step from tens of gallons to hundreds of gallons of 50-percent solid fraction SLH_2 produced. The first large-scale production of SLH_2 was accomplished at the NASA Lewis K-Site facility, in a dewar designed to produce SLH_2 (using the freeze-thaw method) in 800-gal batches. The NASA Lewis SLH_2 production subsystem is shown in Fig. 4. The SLH_2 was produced in solid fractions as high as 65 percent[6] without the use of aging—heat addition to increase the packing density of the SLH_2. It was thought, based on the previous small-scale production studies, that aging would be required to obtain high SLH_2 solid fractions (greater than 40 to 50 percent), but initial large-scale production studies at NASA Lewis obtained high solid fractions without aging. The production of the high solid fraction SLH_2 was a major step in the characterization and understanding of SLH_2 production processes. In a production dewar nearly identical to that used at K-Site, the McDonnell-Douglas Slush Test Facility (STF) demonstrated similar production capabilities.[9] The freeze-thaw method can be modified to enable it to be a continuous production process, although this continuous freeze-thaw process has yet to be demonstrated on a large scale.

The only other production method that has been demonstrated in greater than gallon-size quantities is the auger production method. NIST designed and operated an auger production system at their Boulder, Colorado, facility. A schematic diagram of the auger facility, obtained from Ref. 11, is shown in Fig. 5. The system enabled the auger production of SLH_2 in greater than 150-gal batches. Initial results indicated that auger-produced SLH_2 could be generated at high solid fractions similar to the freeze-thaw method. The auger method enables the continuous production of SLH_2.

There are also safety concerns associated with the production methods. For the freeze-thaw method of production, the dewar is at subatmospheric pressure, which leads to the potential for air in-leakage. Contamination limits and the detection of the air or oxygen in the densified hydrogen still need to be evaluated. The use of welded construction, double flange seals with gaseous helium-purged valve stems at the K-Site and STF production facilities apparently prevented air in-leakage. The auger production method is conducted at pressures above atmospheric pressure, eliminating the major safety issue associated with the freeze-thaw method.

In the area of production, the detailed evaluation of process energy efficiency and capital investment required to support a production plant for NASP or other space applications needs to be completed. Studies are in progress to try to evaluate these aspects of SLH_2 production for the NASP.

Ground Operations

Ground operations can be defined as those operations associated with the hydrogen storage tanks, the transfer of the densified fluid to the vehicle, and the hold period prior to flight (Fig. 6). One issue associated with ground operations is the maintenance of the SLH_2 or TPH_2 during the storage or ground hold period. Because solid hydrogen has a low latent heat (approximately 25 Btu/lb_m), even low heat leak into the ground tanks or the vehicle tank could melt the solid quickly, degrading the solid fraction of the SLH_2. Although TPH_2 has no solid to melt, the temperature of the liquid could increase, reducing the density. Therefore, ground storage tanks and transfer systems should be designed to minimize heat leak, possibly by using liquid helium technology (vacuum-jacketed dewars and lines that use liquid nitrogen cooling to reduce radiation heat losses), to reduce the loss of densified hydrogen.

Because of weight restrictions, the NASP and other space vehicles may not allow for extra insulation systems to reduce the heat leak. In the case of NASP, which has high estimated heat-leak rates, prior to vehicle takeoff the SLH_2 will likely require upgrading by continuous addition of high solid fraction SLH_2 while removing liquid from the fuel tank. The loading and upgrading process can become difficult as maintenance of a constant liquid level would be necessary to prevent overboard discharge of fluid, especially at small ullage volumes. The discharge could occur because the densified hydrogen expands as it degrades and the density decreases. This overboard spilling creates a safety hazard and causes a loss in propellant. Initial loading and upgrading scenario tests for NASP have been performed at the McDonnell-Douglas Slush Test Facility (STF),[9] but it is clear that further work in this area is required. In addition, the SLH_2 solid fraction required at NASP takeoff indicates that a SLH_2 production subsystem (an SLH_2 maintenance unit, or SMU) will be needed. The subsystem must be designed to provide high production rates and be reasonably mobile so that it can be attached to the vehicle for upgrading and then quickly removed prior to flight. Candidates for such a slush maintenance unit include the auger system as well as the magnetic refrigeration unit, which is being considered for liquid hydrogen as well as SLH_2 production.[17] Another option may be a liquid spray technique, described in early work at NIST.[15] Each of these concepts require further development to demonstrate high rates of producing high solid fraction SLH_2. A TPH_2 maintenance system may be easier to design because production of solids is not necessary, but no work has been performed in this area. Development of lightweight, low-heat-leak insulations may reduce some of the maintenance requirements.

An issue related to SLH_2 maintenance is the effect of long-term storage on the SLH_2 characteristics. Early work at NIST[2] showed dramatic changes in the solid hydrogen particle characteristics, such as size and shape, after aging. In an unmixed batch of SLH_2, these changes lead to increases in the SLH_2 solid fraction because of the increased packing fraction. The issue of agglomeration of solids in long-term storage of SLH_2 and the potential need for a mixing system in storage tanks require investigation. Because SLH_2 may also reside in storage tanks in a space-based cryogenic depot for extended periods of time, future studies also are required in this area. These studies could include accelerated aging experiments, where the SLH_2 is subjected to heat addition to change the particle characteristics, evaluation of mixing schemes, and analytical modeling to determine settling and packing during the aging process. In aging testing at K-Site, 50 percent and greater solid fraction SLH_2 was stored without mixing for 8 to 10 hr. The settled solids were easily remixed to a homogeneous SLH_2 mixture.

Another issue associated with ground operations is the transfer of SLH_2 through flow systems. Initial pressurized transfer studies at NIST[2,4] showed that SLH_2 could be transferred through

0.652-in. i.d. tubes as well as through various flow restrictions. This study obtained flow characteristic data as well as critical velocity information for this tube size. (The critical velocity is defined as the velocity at which the solid hydrogen particles begin to settle.) Additional pressurized transfer studies were performed at the STF facility with 1.0-in.-diameter vacuum-jacketed lines[9] and at the K-Site facility with 1.5-in.-diameter vacuum-jacketed lines.[6,8] In these studies it was found that the pressure drop as well as the mixing of the SLH_2 in the generator dewar were important in preventing flow stagnation during SLH_2 transfer. In the K-Site tests, SLH_2 of up to 65-percent solid fraction was successfully transferred, demonstrating the feasibility of transferring high solid fraction SLH_2. In addition, the pre-chill process for the transfer lines and the receiver tank was found to be important in the NASA Lewis te... in preventing loss of SLH_2 during transfer (N... H_2 was used for pre-chilling in these tests). Flow characteristic data (pressure drop versus flow rate) were obtained for both SLH_2 and TPH_2 at the K-Site facility. These data were compared against FLUSH, a NASA Lewis computer model developed to calculate flow characteristic and SLH_2 density losses during transfer.[18] Figure 7 compares the K-Site volumetric flow rate data with the FLUSH analytical predictions, as provided by Ref. 8. As seen in the figure, FLUSH shows close agreement with the experimental data. However, as discussed in Ref. 8, further work is required in predicting density losses with FLUSH because the experimental data showed large variations in density loss (between 0- and 21-percent solid fraction loss).

Experiments have been performed at the STF facility to evaluate pumped transfer of SLH_2. The SLH_2 was successfully pumped from a cylindrical test tank as part of pumped expulsion tests. However, the loss of SLH_2 during the pumped expulsion process must be examined and compared with that obtained in pressurized expulsion tests. High solid fraction loss during pumped transfer may make it an unattractive technique for loading vehicles.

Additional data are required in the area of transfer to address scaling, instrumentation, mixing, and flow modeling. Experimental data for larger flow systems would enable the determination of whether analytical predictions of transfer characteristics, including critical velocity, apply to the larger pipe sizes that may be used for actual vehicle loading. Modification of existing flow models will then be required on the basis of this additional experimental information to allow for scaling predictions. Instrumentation issues include the development of reliable flowmeters and density measuring devices, as will be discussed in following sections of this report. Mixing is important in ground systems to ensure SLH_2 homogeneity for accurate density measurements and to prevent flow stagnation due to solid agglomeration, as shown in the K-Site tests. The types of mixing methods for ground and flight operations still require investigation. Existing flow models are limited to one-dimensional analysis; future efforts in multidimensional modeling could reduce the amount of testing required to obtain information such as critical velocities and density stratification during transfer. Although engineering issues remain in the transfer of SLH_2 and TPH_2, there are no apparent technological barriers in the transfer process.

Flight Operations

Issues associated with the use of densified hydrogen during flight operations include tank pressure control, recirculation, pumping of SLH_2, instrumentation, and flow component modeling. Tank pressure control is an issue because SLH_2 and TPH_2 exist at 1.02 psia. If condensible hydrogen pressurant is used, there is the potential for tank pressure collapse and possible loss of the vehicle if the fuel tanks cannot be designed to accommodate such loads. Helium could be used entirely as the pressurant gas, but this option may present a high weight penalty for the space vehicle, and helium offers no fuel value. Testing at NASA Lewis[6,7] concentrated on the pressure control characteristics during pressurized expulsion of SLH_2 and TPH_2 from a 5-ft-diameter spherical test tank. These tests examined the effect of pressurant gas type, temperature, tank pressure, and fluid mixing on tank pressure control. Similar SLH_2 pressurized expulsion tests were also performed at the McDonnell-Douglas STF facility using a horizontal cylindrical test tank.[9] In the tests at K-Site, the tank pressure did not decrease during the expulsion process, regardless of the pressurant gas type or whether the SLH_2 or TPH_2 was mixed or unmixed. Figure 8 shows an example of a tank pressure profile during the pressurization, hold, and expulsion periods of one NASA Lewis expulsion test with hydrogen pressurant.[7] As shown in the figure, the tank pressure remained essentially constant throughout the test. These K-Site tests represented a key step in demonstrating the feasibility of maintaining tank pressure during the expulsion of SLH_2.

In addition, the pressurant requirements to maintain a constant tank pressure were compared for SLH_2, TPH_2, and $NBPH_2$. As seen in Fig. 9, SLH_2 required the largest amount of pressurant, followed by TPH_2, then $NBPH_2$ in these NASA Lewis tests. Therefore, although tank pressure control appears to be possible when gaseous hydrogen is used during expulsion, the pressurant requirements will increase when densified hydrogen is used. These expulsion tests also showed that adding helium during tank pressurization prior to expulsion, then using gaseous hydrogen to maintain tank pressure during expulsion, significantly reduces the pressurant requirements.

Tank pressure can apparently be controlled during pressurized expulsions of SLH_2 and TPH_2. However, further testing is required to determine whether tank pressure can be controlled during pressurization and expulsion when rapid fluid movement, or sloshing, occurs. Sloshing could eliminate the thermal stratification that normally occurs in the tank, causing increased condensation of hydrogen pressurant, thus leading to the possibility of pressure collapse.

In the NASP vehicle there may be times when the hydrogen cooling requirements exceed the propulsion requirements. As described in Ref. 13, if this extra hydrogen is routed through the propulsion system, the overall performance of the system may significantly decline even though the thrust produced may increase. An option would be to condense the extra gaseous hydrogen by injecting the gas directly into the SLH_2 or TPH_2 fuel, thereby decreasing the total propellant requirements on the NASP vehicle. This process, called recirculation, could decrease the vehicle weight by reducing the propellant requirements. Recirculation was investigated in experiments at NASA Lewis with SLH_2 and $NBPH_2$. From these initial tests it appeared that, under certain conditions, tank pressure could not be maintained during expulsions with submerged gas injection. On the basis of the K-Site tests, further experimental and analytical investigations are necessary prior to the use of recirculation on the NASP vehicle, especially in designing the recirculation gas injection apparatus.

Although pressurized transfer may be desired for ground operations, pumped expulsion and transfer will be used on vehicles such as the NASP. The advantage of pumped expulsion would be decreased pressurant requirements. The SLH_2 will be pumped in the NASP to meet the coolant and propellant needs. The pumping of the SLH_2 will melt the solids, but the liquid will still be at a lower temperature than normal boiling point liquid, and thus will provide greater cooling than $NBPH_2$. Data obtained at NIST[19] showed that SLH_2 and TPH_2 could be pumped with no dependence of pumping efficiency, net positive suction head, or pump wear on the fluid type. It must be determined whether the SLH_2 and TPH_2 pumping test results obtained by NIST and more recently at STF (see ground operations section) apply to other types and sizes of pumps that may be used for space vehicle applications.

Instrumentation for SLH_2 has also been investigated under the NASP program. In the initial phases of the NASP program, a study was performed by NIST to survey available cryogenic instrumentation.[20] The study focused on the measurement of density, flow rate, liquid level, and temperature. Density measurements can be especially difficult in a vehicle tank where a significant number of obstacles, such as baffles, exist. Nuclear radiation attenuation devices have been used in the K-Site, STF, and NIST testing to measure SLH_2 density. In addition, capacitance devices have been used at the K-Site facility and are under development at Ball Aerospace.[21] Although these devices have been used in laboratory environments, much development work is necessary for these devices to attain the high levels of accuracy required for flight-type applications. In addition, calibration methods are required for determining the accuracy of the density measurement options, and a mixing system may be required for accurate density measurements because the measurement of SLH_2 density is highly sample dependent. Alternate methods for determining overall vehicle fluid density do exist, however. For example, it also is possible that the fuel load may be determined by weighing the vehicle, rather than by developing and demonstrating a new device. Investigation of alternate methods may be required in future SLH_2 applications.

Flow rate measurement instrumentation also needs to be developed. No work has been performed under the NASP program in the area of instantaneous flow rate measurement of densified hydrogen. Promising approaches to flow measurement include Coriolis effect mass flowmeters and turbine flowmeters. Mass flow metering presents more of a challenge because accurate density measurements are required. Capacitance liquid level probes were used at the K-Site facility with few problems. However, variations in level measurements during the production process at the STF indicate that further work in this area may be necessary. Silicon diode temperature sensors appear to provide accurate measurements of temperatures for SLH_2 and TPH_2 testing, and existing pressure-sensing devices can be used for these fluids.

Finally, flow component modeling is required for the fuel system lines and the tanks to allow for scaling prior to development of the space vehicle and to reduce the testing required prior to building hardware. Modeling efforts with FLUSH have been discussed for the flow line transfer characteristics. Additional efforts under the NASP program led to the development of codes at NASA Lewis for prediction of ullage gas thermal stratification, pressurant requirements, and solid hydrogen losses during the pressurization and expulsion of SLH_2.[22,23] Figure 10 compares the experimental wall and ullage gas temperature profiles with those predicted by the EXPL code. EXPL is a NASA Lewis code which calculates one-dimensional thermodynamics parameters during tank expulsion. As seen in the figure, EXPL shows close comparison to the experimental data. These models are being verified by data obtained from the 5-ft-diameter spherical test tank at K-Site. This data verification also will assist in the understanding of the mechanisms that transfer heat to densified hydrogen fuels. Further data from tanks with various geometries would enable full validation of these codes.

Most of the modeling efforts under the NASP program have concentrated on developing one-dimensional design models. However, because of the potential for multidimensional thermodynamic and fluid dynamic effects, modeling is also required in two and three dimensions. Efforts at NASA Lewis[24] and Memphis State University[25] were conducted to study the multidimensional thermodynamic effects during tank pressurization. Figure 11 (obtained from Ref. 31) shows the effect of gravitational forces on the tank pressurization process as predicted by the FLOW-3D model. FLOW-3D is a code developed by Flow Science, Inc., to calculate multidimensional fluid dynamics and heat transfer. As shown in the figure, as the gravitational level is reduced, the temperature profiles become more dependent on radial direction. These results would imply that ground testing may not produce the same results as those obtained in low-gravity environments, pointing to the need for alternate testing techniques. In addition to thermodynamic effects, fluid dynamic effects must be considered. Efforts at McDonnell-Douglas[26] have shown flow field predictions in a fluid with solid particles. This becomes especially important when sloshing is considered, as shown by the analytical work performed at McDonnell-Douglas.

Safety

The issue of safe handling of SLH_2 and TPH_2 is applicable to production, ground handling, and flight operations. Los Alamos National Laboratory performed the initial work in developing the criteria for safe handling of SLH_2 as part of the NASP program. Los Alamos performed a literature survey to determine available safety information and conducted reviews with industry and government to obtain information not available in the open literature. Several safety issues were delineated from this study. One major safety concern is pressure control, which was discussed in previous sections on production and flight operations. Volume expansion is another issue, as discussed in the previous ground operations section. Also, detection of air in-leakage and the degree of hazard associated with air in SLH_2 or TPH_2 require further study. The NASA hydrogen safety manual was updated to include a chapter by Los Alamos on SLH_2 as part of this effort.[27] This update served as the initial development of a set of safety criteria. Further criteria will be determined as additional data on densified hydrogen handling become available.

Concluding Remarks

Slush hydrogen and triple-point hydrogen offer potential benefits because of the increased density and heat capacity of these fuels in comparison to normal-boiling-point hydrogen. The potential benefits for the National Aero-Space Plane (NASP) include reduced vehicle size and weight, thus enabling the various missions envisioned for the NASP. Slush hydrogen and triple-point hydrogen benefits have also been quantified for additional space missions including Earth-to-orbit transfer, planetary exploration, and cryogenic depots. These cryogenic fluids offer the potential for reduced vehicle weight, increased payload, or longer fuel storage times in orbit, depending on the particular mission. Therefore, the use of densified hydrogen appears to be attractive for various space missions.

Before slush hydrogen or triple-point hydrogen can be used on space vehicles, several issues must be resolved. Under the NASP program an experimental and analytical effort has been performed to quantify the handling characteristics of the densified hydrogen fuels. This effort has provided extensive handling experience with slush hydrogen and triple-point hydrogen. From the results of this program, to date it appears that no technological breakthroughs are required for the use of slush hydrogen or triple-point hydrogen. Technology issues still to be resolved include fuel tank pressure control under sloshing conditions, the behavior of the fluids under a reduced gravity environment, and the verification that existing mathematical models can be used to fully characterize the thermodynamics and fluid dynamics of slush hydrogen when the tankage is scaled to larger sizes. In addition, the cost and efficiency of a slush hydrogen production plant must still be determined. It appears, however, that most of the technology issues can be solved through continued engineering and research studies on densified hydrogen fuels.

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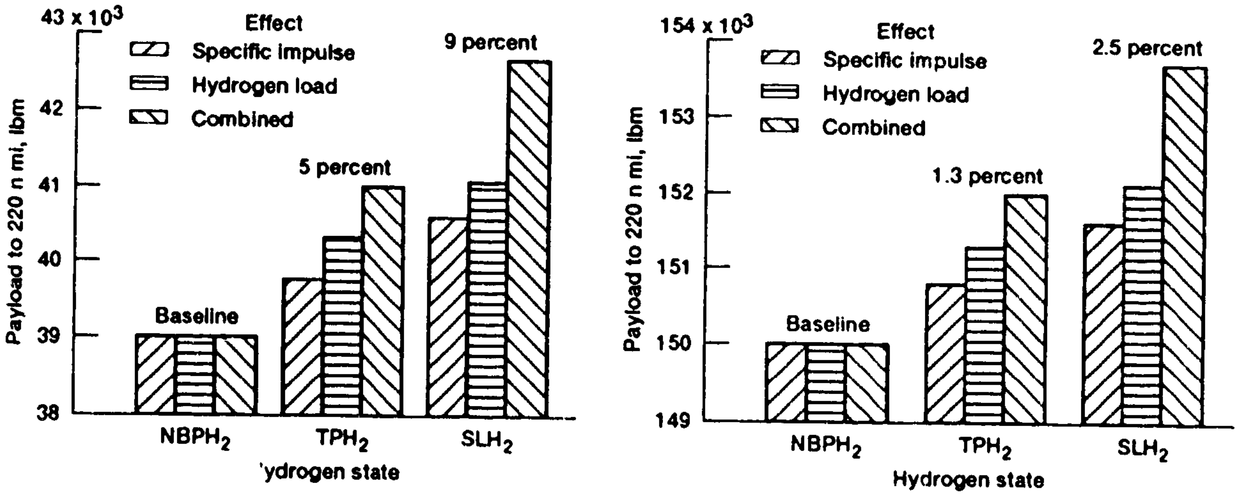
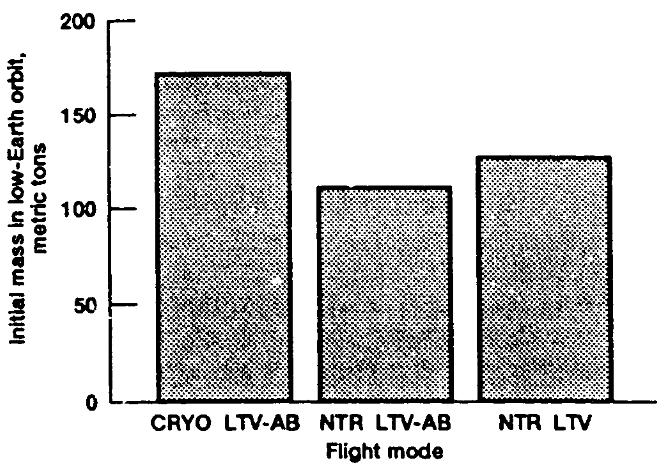
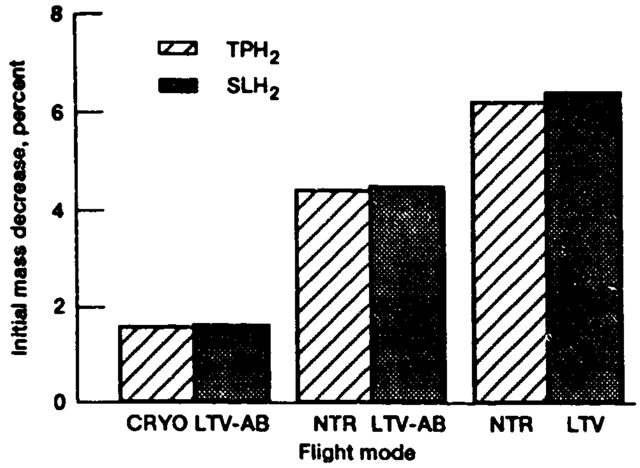


(a) Shuttle (STS). (b) Shuttle-cargo (STS-C).

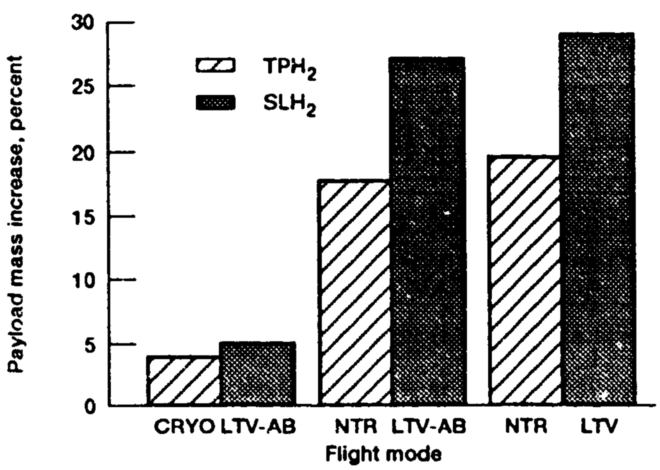
Fig. 1. Payload gain with normal-boiling-point ($NBPH_2$), triple-point (TPH2), and slush hydrogen SLH_2).



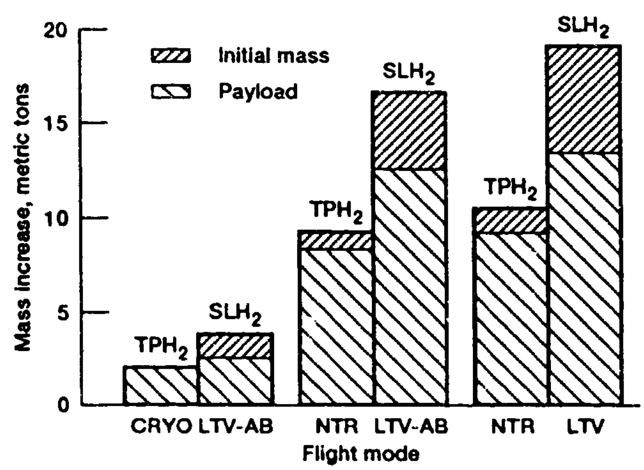
(a) Performance with normal-boiling-point hydrogen. Outbound payload, 46 metric tons; inbound payload, 6.6 metric tons.



(b) Mass savings at constant payload.



(c) Payload gain at constant tank volume.



(d) Mass difference at constant tank volume.

Fig. 2. Hydrogen-state performance comparison for Lunar Outpost Mission. (Cryogenic O/H lunar transfer vehicle with aerobrake (CRYO LTV-AB), nuclear thermal propulsion system with aerobrake return (NTR LTV-AB), nuclear thermal propulsion system with propulsive return (NTR-LTV), nuclear thermal propulsion system (NTR), and lunar transfer vehicle (LTV).)

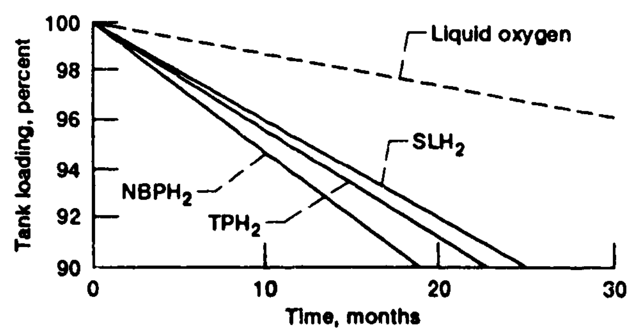


Fig. 3. Boiloff as a function of storage time (cryogenic oxygen/hydrogen depot).

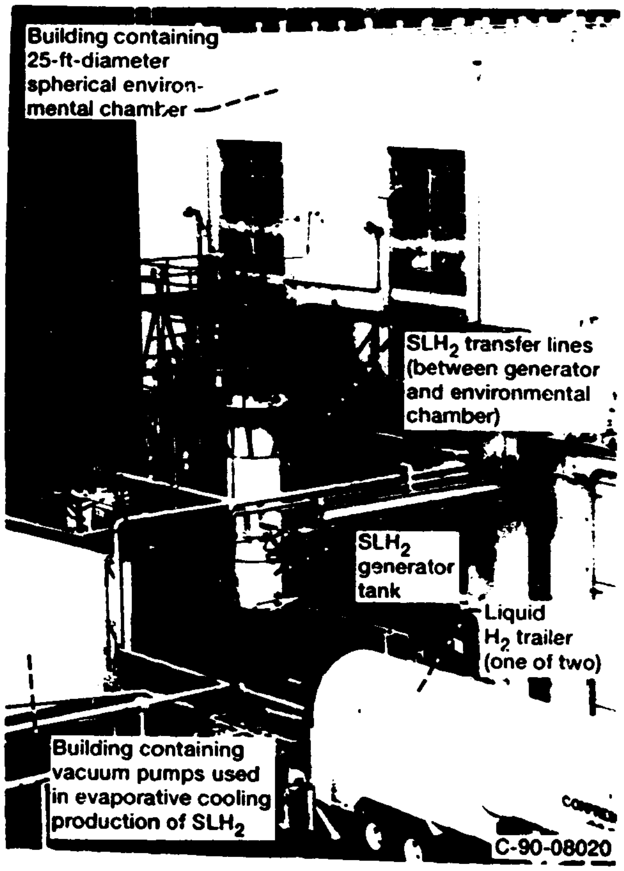


Fig. 4. NASA Lewis Research Center SLH_2 production subsystem at Plum Brook Station.

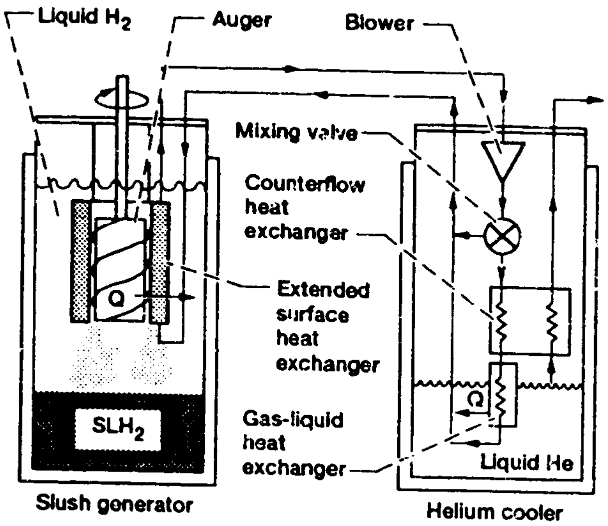


Fig. 5. Auger slush hydrogen generator and cooler (from Ref. 11).

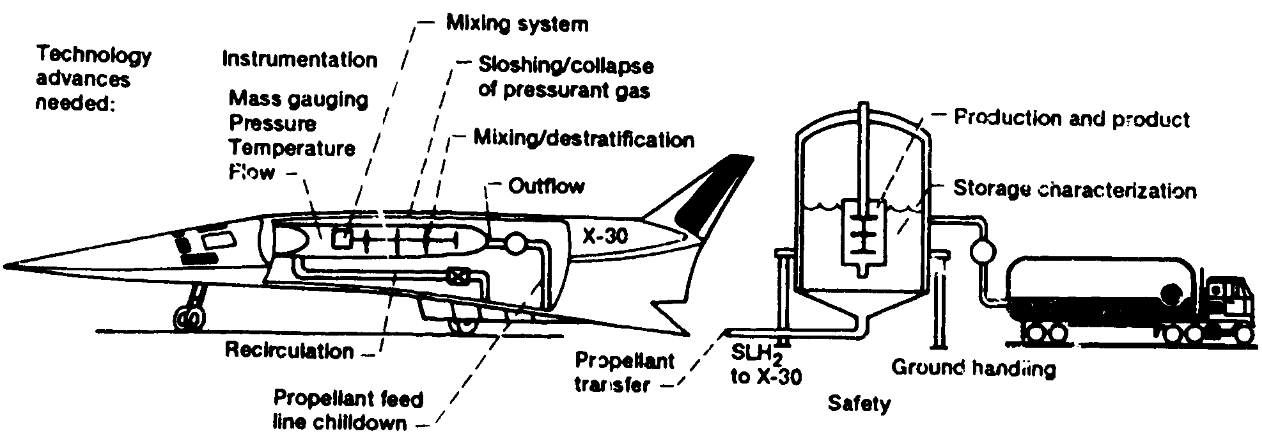


Fig. 6. Technology advances required for slush hydrogen ground and flight systems.

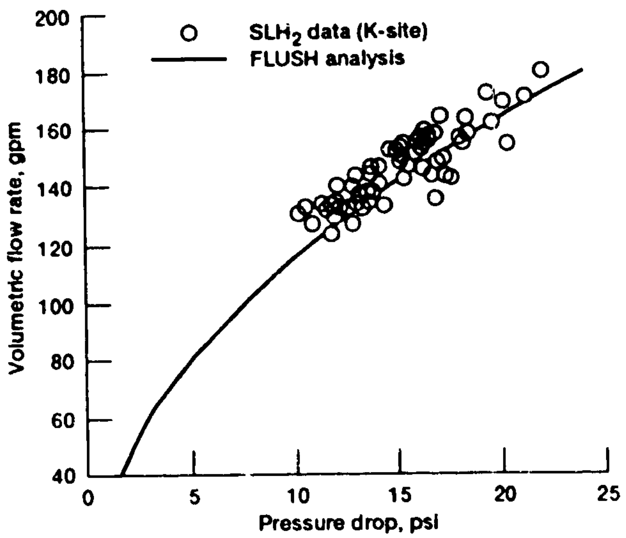


Fig. 7. Comparison of slush hydrogen volumetric flow rate data with FLUSH analysis.[8]

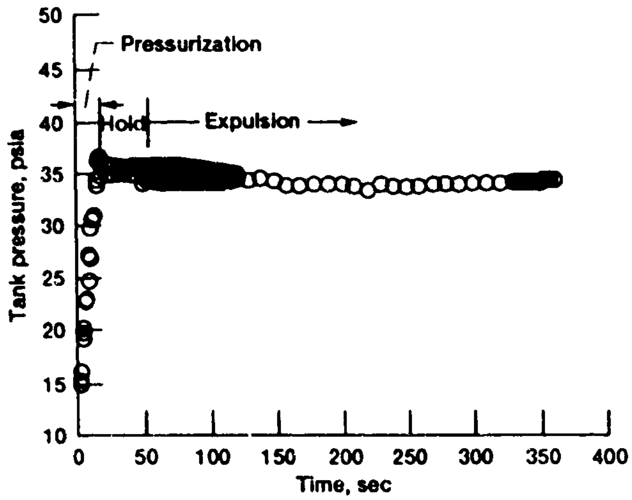


Fig. 8. Slush hydrogen pressurized expulsion—tank pressure profile. Run 2302; reading number 614; hydrogen pressurant at 541 °R.

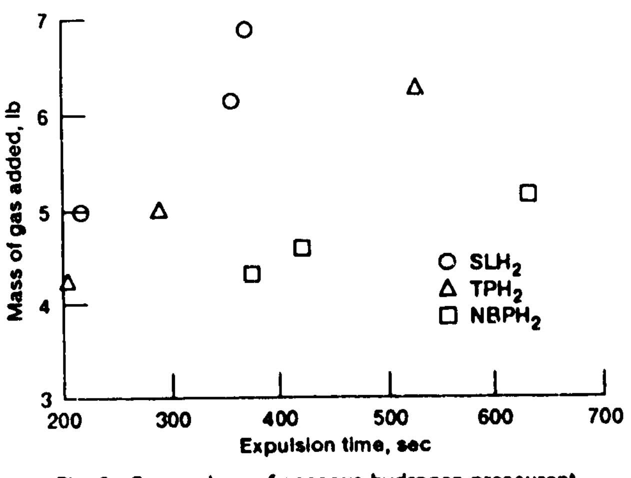


Fig. 9. Comparison of gaseous hydrogen pressurant requirements. Expulsion pressure, 35 psia; gas temperature, 250 °R.

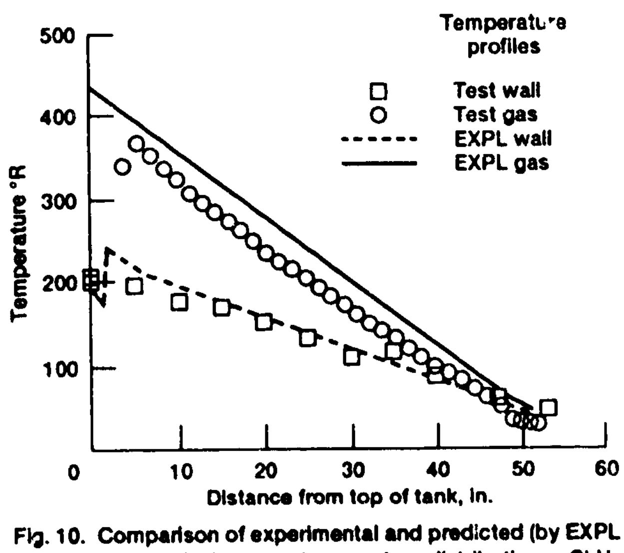
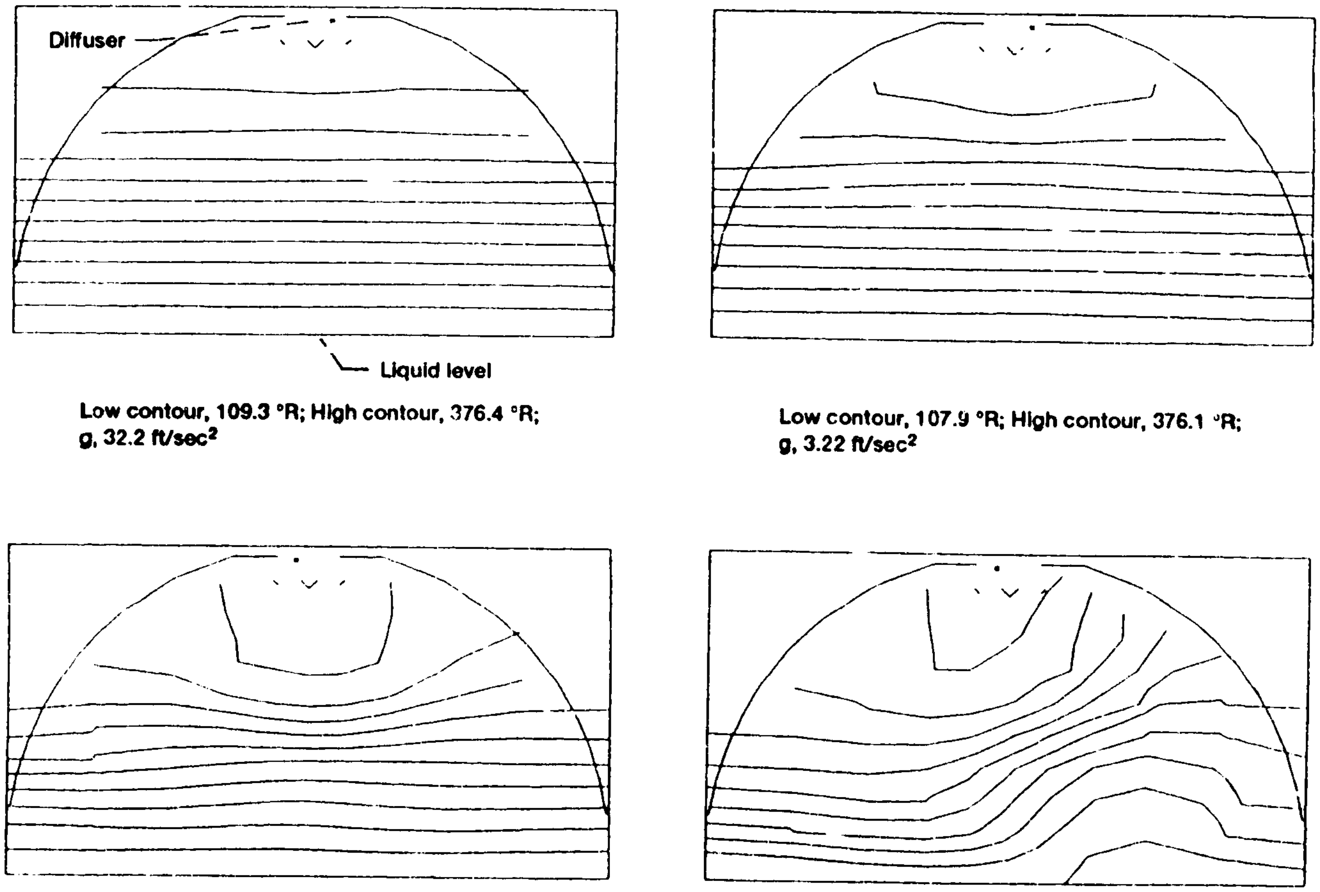


Fig. 10. Comparison of experimental and predicted (by EXPL model) wall and ullage gas temperature distributions. SLH$_2$ expulsion; run 315; reading number 268; 190-sec expulsion at 48.7 psia; gas temperature, 518 °R.



Low contour, 109.3 °R; High contour, 376.4 °R; g, 32.2 ft/sec²

Low contour, 107.9 °R; High contour, 376.1 °R; g, 3.22 ft/sec²

Low contour, 107.4 °R; High contour, 375.4 °R; g, 0.322 ft/sec²

Low contour, 103.3 °R; High contour, 374.6 °R; g, 0.0 ft/sec²

Fig. 11. Flow-3D predictions of effect of gravitation force on temperature contours during slush hydrogen pressurization. Ullage, 55 percent; pressurization, 24 sec; initial pressure, 17.4 psia.[24]

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13. ABSTRACT *(Maximum 200 words)*

Slush hydrogen and triple-point hydrogen offer the potential for reducing the size and weight of future space vehicles because these fluids have greater densities than normal-boiling-point liquid hydrogen. In addition, these fluids have greater heat capacities, which make them attractive fuels for such applications as the National Aero-Space Plane and cryogenic depots. Some of the benefits of using slush hydrogen and triple-point hydrogen for space missions are quantified in this report. This report also examines some of the major issues associated with using these densified cryogenic fuels for space applications and summarizes the technology efforts that have been made to address many of these issues.

14. SUBJECT TERMS
Hydrogen; Slush hydrogen; Liquid hydrogen; Cryogenic fluids; Cryogenics; Space missions; National Aero-Space Plane Program

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