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COMPARISON OF SUPER-HIGH-ENERGY-PROPULSION-SYSTEMS BASED ON METALLIC HYDROGEN PROPELLANT FOR ES TO LEO SPACE TRANSPORTATION

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ABSTRACT

This paper investigates the application of metallic hydrogen as rocket propellant, which contains a specific energy of about 52 kcal/g in theory yielding a maximum specific impulse of 1700 s. With the convincing advantage of having a density fourteen times that of conventional liquid hydrogen/liquid oxygen propellants, metallic hydrogen could satisfy the demands of advanced launch vehicle propulsion for the next millennium.

Provided, that there is an atomic metallic state of hydrogen, and that this state will be metastable at ambient pressure, which is still not proven, the present publication shows the results of the investigation of some important problem areas, which concern the production of metallic hydrogen, the combustion, chamber cooling and storage.

The results show, that the use of metallic hydrogen as rocket propellant could lead to revolutionary changes in space vehicle philosophy towards small size, small weight and high performance SSTO system: The use of high metallic hydrogen mass fractions results in a dramatic reduction of required propellant volume, while gas temperatures in the combustion chamber exceed 5000 K. Furthermore it follows from this study, that hydrogen (liquid or slush) is the most favourable candidate as working fluid. However, jet generated noise has to come into intense consideration, due to the very high exhaust velocities, which are possible with metallic hydrogen propellant.

Symbols and abbreviations:

Ce : Exhaust velocity
DV : Velocity increment
Hmet : Metallic hydrogen
LHmet : Liquid metallic hydrogen
SHmet : Solid metallic hydrogen
MA : Methyl alcohol
M0 : Overall launch mass
M1 : Payload mass
M8 : Propellant mass
Mn : Vehicle dry mass
LH2 : Liquid hydrogen
SLH2 : Slush hydrogen
SH2 : Solid hydrogen
RP1 : Rocket propellant number one

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1. INTRODUCTION

During the last thirty years space technology became a more and more economic factor in many areas. In particular, in the fields of ES-LEO transportation systems but also in many fields of satellites applications the aspect of competitiveness gained in significance. Against the background of the expected increasing space activities in number during the next decades, assisted by the establishment of growing space stations as well as by expanded missions to other celestial bodies up to its colonization (moon and mars), the following aspects concerning the realization of those space projects should be regarded with priority:

a) Reduction of the specific transportation costs ($/kg-payload) by the factor 10 from today's level (about 25000 to 40000 $/kg)
b) Increase of space transportation capacities
c) Increase of space transportation vehicle performance
d) Reduction of negative implications to the environment (noise, power, exhaust gas reactions with ambient air, required propellant mass per kg payload, etc.)
e) Increase of reliability

In view of these demands, the propulsion system represents the decisive influencing component of launchers. The performance of a rocket engine itself will be mainly influenced from the quality of the used propellant combination, which is characterized primarily by the specific impulse.
Tab.1-1: General correlation between propellant performance and main launch vehicle parameters

In Tab.1-1 the effects of the realizable specific impulse on the characteristic performance parameters of launch systems is shown. A diminishing value of the engine performance parameter DV/Ce (corresponding to challenge c) as well as increasing lightweight construction capability lead to increasing payload ratios (M1/M0) and therewith to increasing space transportation capacities (corresponding to challenge b). Increased payload mass ratios could lead to reduced specific transportation costs (corresponding to challenge a).

As may be seen below, the use of super high energy propellants could reduce the propellant consumption considerably, in the course of which metallic hydrogen represents the most promising candidate. The interest of this study into metallic hydrogen as rocket propellant is based on the very high energy content, which is equivalent to high theoretical performance, which in turn is indicated by the specific impulse. The specific impulse formula used, is as function of the overall net energy release per unit mass of propellant and is derived from the equation of the ideal exhaust velocity of a gas after thermodynamic expansion. Introducing an overall efficiency factor for the energy conversion (as a function of the ratio of specific heats, k, and pressure ratio, Pe/Pc) lead to:

\[ Isp = \frac{(2h + Q)}{g} \times \frac{1}{s} \]
The metallic hydrogen story

PRACTICAL RESEARCH EFFORTS

- Expansion of practical hydrogen gas at room temperature up to 1000 bars
- Transition of material observed at 373 K (100 °C) and electrical resistance increases
- Onset of superconductivity observed

THEORETICAL RESEARCH EFFORTS

- Calculations show the presence of metallic, state-of-matter hydrogen production at high temperatures (100 K, the mean)
- Propagation of metallic hydrogen

Fig. 2-1: Development of research efforts in the field of metallic hydrogen over the years

3. MAIN RESEARCH EFFORTS

The present investigations will give a general idea of metallic hydrogen propellant application. Due to the wide range of investigation areas, only those will be presented, which have been identified as the most interesting ones. Fig. 3-1 illustrates the main research efforts.

Tab. 2-1: Properties of metallic hydrogen; properties important for this study are marked

<table>
<thead>
<tr>
<th>Property</th>
<th>Value (10)</th>
<th>Value (14)</th>
<th>Value (15)</th>
</tr>
</thead>
<tbody>
<tr>
<td>State of aggregation</td>
<td>solid</td>
<td>solid</td>
<td>solid</td>
</tr>
<tr>
<td>Source energy (100%)</td>
<td>55 (55)</td>
<td>(3)</td>
<td>(13)</td>
</tr>
<tr>
<td>Density</td>
<td>1.35 g/cm³</td>
<td>1.38 g/cm³</td>
<td>1.38 g/cm³</td>
</tr>
<tr>
<td>Storage temperature</td>
<td>700 K (14)</td>
<td>77 K (14)</td>
<td>77 K (14)</td>
</tr>
<tr>
<td>Storing pressure</td>
<td>2.5 Mbar</td>
<td>2.5 Mbar</td>
<td>2.5 Mbar</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>2.69 g/cm³</td>
<td>2.70 g/cm³</td>
<td>2.70 g/cm³</td>
</tr>
<tr>
<td>Large volume factor</td>
<td>10 (15)</td>
<td>10 (15)</td>
<td>10 (15)</td>
</tr>
<tr>
<td>Molecular diameter</td>
<td>8.3 (10)</td>
<td>8.3 (10)</td>
<td>8.3 (10)</td>
</tr>
<tr>
<td>Supercritical maximum</td>
<td>not reported</td>
<td>not reported</td>
<td>not reported</td>
</tr>
<tr>
<td>Critical properties</td>
<td>not reported</td>
<td>not reported</td>
<td>not reported</td>
</tr>
<tr>
<td>Supercritical maximum</td>
<td>2.5 Mbar</td>
<td>2.5 Mbar</td>
<td>2.5 Mbar</td>
</tr>
<tr>
<td>Transition in pressure</td>
<td>2.5-3.5 Mbar</td>
<td>2.5-3.5 Mbar</td>
<td>2.5-3.5 Mbar</td>
</tr>
<tr>
<td>Melting point in solid</td>
<td>not reported</td>
<td>not reported</td>
<td>not reported</td>
</tr>
<tr>
<td>Melting point in liquid</td>
<td>not reported</td>
<td>not reported</td>
<td>not reported</td>
</tr>
</tbody>
</table>

The present investigations will give a general idea of metallic hydrogen propellant application. Due to the wide range of investigation areas, only those will be presented, which have been identified as the most interesting ones. Fig. 3-1 illustrates the main research efforts.

Fig. 3-1: Main research efforts
3.1 CHOICE OF PROPELLANT COMBINATIONS

Due to the very high energetics of metallic hydrogen, yielding very high thrust chamber gas temperatures (as may be seen later), a secondary propellant component is required, which absorbs the heat of reaction and serves as expansion medium. The choice of the right working fluid should be done against the background of the general known propellant features.

Besides the combination of Hmet/LH2 as presented in the introduction, the following investigations include also more dense elements like slush hydrogen SLH2 and solid hydrogen SH2 which are cryogenic fuels, but also storable ones like the conventional used rocket propellant RP1 and another candidate, namely methyl alcohol, which offers higher performances compared to RP1. Tab. 3-1 lists the basic data of the investigated reactants fuels.

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Formula</th>
<th>Enthalpy (cal/mole)</th>
<th>Phase</th>
<th>Temp.(K)</th>
<th>Density (g/cc)</th>
<th>Satur.</th>
<th>Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>H2</td>
<td>2714</td>
<td>liquid</td>
<td>90.0</td>
<td>0.100</td>
<td>121</td>
<td>2</td>
</tr>
<tr>
<td>RP1</td>
<td>C11H623</td>
<td>-4560</td>
<td>liquid</td>
<td>298.15</td>
<td>0.771</td>
<td>121</td>
<td>2</td>
</tr>
<tr>
<td>Methyl alcohol</td>
<td>C4H10</td>
<td>-9540</td>
<td>liquid</td>
<td>298.15</td>
<td>0.786</td>
<td>121</td>
<td>2</td>
</tr>
</tbody>
</table>

Tab.3-1: Reactants fuels data

The choice of the propellant combinations determines the tankage concept. For lack of data about metallic hydrogen properties (will it be a liquid or a solid?, storage temperature?, etc. as explained in chapter 3) various possible propellant combinations alternatives have been regarded. They are listed in Tab.3-2 (where -P stands for powder, -G stands for grain). The marked propellant combinations (P-x) will be analyzed below.

<table>
<thead>
<tr>
<th>Hmet</th>
<th>LH2</th>
<th>RP1</th>
<th>MA</th>
<th>SLH2</th>
<th>SH2</th>
<th>SLH2</th>
<th>SIFmet</th>
<th>SIFmet</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC1</td>
<td>PC2</td>
<td>PC3</td>
<td>PC4</td>
<td>PC5</td>
<td>PC6</td>
<td>PC7</td>
<td>PC8</td>
<td>PC9</td>
</tr>
</tbody>
</table>

Tab.3-2: Investigated propellant combinations

3.2 THRUST CHAMBER PERFORMANCE PARAMETERS

The thrust chamber is the basic element of a chemical rocket engine. Typical chamber parameters (defined in Tab.3-3) are shown in the following figures 3-2 to 3-6, based on thermochemical computations which equate the heat of reaction of the propellant combinations and the rise in enthalpy of the combustion gases at frozen composition [16].

All parameters are plotted against the metallic hydrogen mass fraction (respectively weight fraction). All data are given for 68:1 expansion ratio. The energy storing capacity of the propellant gas molecules is indicated by the specific heat ratio. Increasing values of \( \kappa \) indicate decreasing energy storage capabilities, due to a lower number of degrees of freedoms, and in turn gives lower engine performance.

Increasing atomic hydrogen weight fractions in the propellant yield higher thrust chamber gas temperatures and thus, will lead to higher atomic hydrogen mol fractions of the combustion gases. Simple atoms, however, have only three translational degrees of freedom, and hence, yield lower specific heats, which results in increasing values for \( \kappa \).

As may be seen from figures 3-3,4, the vacuum specific impulses of the systems Hmet/RP1 increases nearly linear for a wide range of Hmet weight fractions (nearly the same for system Hmet/MA), compared to the system Hmet/LH2. Moreover a very high temperature level is reached very soon with increasing Hmet weight fraction, compared to the system Hmet/LH2, which yields a more constant gradient for the temperature curve. Increased chamber pressures shift the curve to higher values for all combinations.
The gas temperatures of the systems Hmet/MA, Hmet/RP1 indicate a combustion process of higher energy and efficiency corresponding to a lower value of propellant consumption.

Hydrogen as working fluid represents the best alternative due to highest values for both, characteristic velocity and vac. specific impulse, at low Hmet weight fractions.

The computations of the characteristic velocities yield the following results:
• The higher values of the characteristic velocity in the sequence H2, MA, RP1 indicate a combustion process of higher energy and efficiency corresponding to a lower value of propellant consumption.

The results of the computation of the volume specific impulse are:
• The more dense working fluids RP1 and MA shows an impressive advantage concerning tank volume reductions, compared to hydrogen, which yields no more than 430 kg/m^3 of bulk density even with 90% Hmet.
• Therefore the density impulses are much higher, using RP1 or MA as working fluids.

To give a comparison of the combustion behaviors between the metallic hydrogen propellant combinations and other conventional liquid propellant combinations used today, the vac. specific impulse and gas temperature are plotted in Fig. 3-7. If the specific impulse with metallic hydrogen combustion is fixed on the level of the conventional high energetic combinations (LOX/LH2, LOX/F2), the gas temperatures will be lower. In the case of the constant gas temperature, the specific impulses are much higher.

Results:
• There are lower thermal risks of thrust chamber due to lower chamber temperatures, if metallic hydrogen propulsion is used in the realm of conventional specific impulses (low percentages of metallic hydrogen).
• An enormous increase in specific impulse arises, if chamber temperatures are not kept within conventional limits.
• The combination using hydrogen as working fluid shows the most extreme behavior in this sense.
3.3. THRUST CHAMBER COOLING

In the case of the investigation of the metallic hydrogen fraction above 15% for the system Hmet/MA and Hmet/RP1 respectively above 40% for Hmet/LH2 the chamber temperatures will increase over the values for the conventional propellant combinations which lies in the range between 2500 K and 3700 K. Because of the high heat transfer rates from the hot gases to the chamber wall, thrust chamber cooling becomes a major design consideration. The objective was to investigate the influences of gas temperatures, arising from Hmet-combustion, on chamber cooling demands. The results can only be regarded as simple approximations.

Fig.3-9 shows schematically the cooling problem, which is basically one of heat and mass transport associated with conduction through a wall. It can be treated as a series type heat-transfer problem.

The general steady-state heat-transfer equation can be expressed as follows:

\[ q = H(T_g - T_l) = Q / A \]

where

- \( q \): heat flux or heat transferred per unit area per unit time [W/m²]
- \( H \): Overall film coefficient or overall heat transfer coefficient [W/m²·K]
- \( T_g \): Absolute chamber gas temperature [K]
- \( T_l \): Absolute coolant liquid temperature [K]
- \( Q \): Heat transferred per unit time [W] across a surface A [m²]

The determination of the overall film coefficient \( H \) is a rather complex problem. It can be expressed as follows:

\[ H = 1 / (1 / h_g + 1 / h_c) \]

where

- \( h_g \): Chamber wall thickness [m]
- \( k \): Thermal conductivity of chamber wall [W/m·K]
- \( h_c \): Gas film coefficient [W/m²·K]
- \( h_c \): Coolant liquid film coefficient [W/m²·K]

\( H \) is composed of the individual coefficients for the boundary layers and the chamber wall. The smaller \( H \), the smaller is \( q \). It is one of the major design goals to keep gas side heat transfer coefficient \( h_g \) low, but the coolant liquid heat transfer coefficient and conductivity \( k \) high, in relation to \( h_c \). The cooling problem will be analysed in a very simple manner, based on the given data for \( q \) and \( H \) of the SSME thrust chamber. It will simply be answered, how much the cooling parameters \( q \) and \( H \) will change relative to the SSME data, as function of the relative change of chamber temperature (which is in turn dependent on Hmet weight fraction).

The following Table 3-4 states the most important material parameters exemplary for the SSME, which uses the today's most developed integral CuFeZr design.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Integral CuFeZr design of SSME</th>
<th>Tendency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity</td>
<td>W/m·K</td>
<td>0.5</td>
<td>should be low</td>
</tr>
<tr>
<td>Coefficient of thermal expansion</td>
<td>K/°C·K</td>
<td>1.65</td>
<td>should be low</td>
</tr>
<tr>
<td>Wall thickness</td>
<td>cm</td>
<td>0.07</td>
<td>should be low</td>
</tr>
<tr>
<td>Overall film coefficient</td>
<td>W/m²·K</td>
<td>8.797</td>
<td>should be high</td>
</tr>
<tr>
<td>Thermal properties of outer shell</td>
<td>W/m²·K</td>
<td>-</td>
<td>should be high</td>
</tr>
<tr>
<td>Max. heat flux ( q )</td>
<td>W/m²</td>
<td>38,000</td>
<td>(for outer shell=75%)</td>
</tr>
</tbody>
</table>

Tab.3-4: SSME chamber material parameters and overall tendency

Fig.3-10,11 gives an impression of the cooling difficulties induced by chamber temperatures above today's levels. The percent changes of the heat flux, \( dq \), the temperature drops from absolute chamber gas temperature to the absolute liquid coolant temperature, \( dT \), and the change of the overall film coefficient, \( dH \), are plotted over the change of metallic hydrogen weight fraction for the combinations Hmet/LH2 (Fig.3-10) and Hmet/MA (Fig.3-11).

The zero-line represents the SSME technology with chamber temperature of \( T_c = 3637 \) K and coolant liquid temperature of \( T_l = 420 \) K. The changes for \( dq \) have been computed for constant \( dH \) and just the other way round, based on the general steady-state heat transfer equation. It should be noted here, that this approxi-
The change of premises indicate the beginning of the range, marking increased technology requirements for the chamber materials (at the point, where thought lines of communication between the bars are crossing the zero-line). This critical range begins for metallic hydrogen fractions above 30 per cent with Hmet/LH2 propellant combination and above 5 per cent with Hmet/MA due to increasing chamber temperature.

This means for example that 50% Hmet in a Hmet/LH2 propellant yields a temperature drop of 52.9 per cent above the reference value for the SSME. This can be realized either by 40 per cent increase of the heat flux compared to the SSME with constant overall film coefficient, or by 25.5 per cent decrease of the overall film coefficient with constant heat flux capability. It is obvious that tremendous efforts in the fields of material research are necessary yielding material properties capable of meeting those demands.

On the other hand, Fig.3-10 gives the positive result, that today's cooling technology will be sufficient up to 30 per cent of Hmet fraction, representing the potential for low cost chamber technology.

Results:
- The propellant systems Hmet/LH2 and Hmet/MA shows different behaviors concerning cooling requirements.
- Today's cooling technology is applicable up to 30% Hmet for system Hmet/LH2.
- Today's cooling technology is applicable only up to 5% Hmet for the system Hmet/MA.

These values are optimistic.
- The system Hmet/LH2 offers a great potential for cost savings of chamber and cooling technology if Hmet fractions beneath 40% are chosen due to their low chamber temperatures.
- The system Hmet/MA offers constant cooling conditions in the range between 20% and 60% Hmet weight fraction.
- Enhanced research towards materials with increased thermal conductivity and low thermal expansion coefficients is required.
- Further investigations concerning gas side heat transfer minimization and coolant side heat transfer maximization are necessary.
3.4 STORAGE CONCEPTS

This chapter contains parametric results of some reflections on basic design configurations of propellant tanks. These investigations base on the assumption of metallic hydrogen being stable at all pressures and in all different states of aggregation.

3.4.1 Influence on propellant volumes

An important propellant parameter is their density. High densities are desirable to minimize the size and weight of propellant tanks and feed systems.

The Hmet weight fraction dependent storage volumes for the propellant combinations Hmet/LH2, SLH2, SH2, RP1, MA have been computed for different payload masses (5 Mg, 20 Mg and 200 Mg) for a 9300 m/s-SSTO-vehicle mission. Absolute values have been connected with corresponding values for a conventional LOX/LH2 system (O/F=5; Expansion ratio 68:1; eq. flow) yielding 4111.67 m/s specific vacuum impulse. In Fig.3-12 the propellant volume fractions are plotted over the Hmet weight fraction for the different propellant combinations.

Fig.3-12: Relative changes of propellant volume with metallic hydrogen weight fraction; factors at vertical axis indicate the change to the corresponding values for LOX/LH2 system

All line points above a volume fraction of one are not as good as the conventional LOX/LH2 system, they have larger volumes. All line points below a volume fraction of one represent potential mass reductions. Hmet weight fractions above 17% yield propellant volume reductions, compared to conventional systems.

In Fig.3-13 the volumes data are expressed in terms of diameters of spherical tanks to increase the vividness.

Results:

- If hydrogen in liquid, slush or solid state is used as secondary propellant component at least 15%, 16 respectively 17% metallic hydrogen weight fraction is required to be smaller in propellant tank volume compared to the conventional LOX/LH2 system.
- Most effective reductions in propellant volumes are achievable with methyl alcohol and RP1 as secondary component. Less than 10% Hmet weight fraction will be sufficient.
- 40% Hmet weight fraction yield propellant volume reductions less than a factor of 0.5 for all systems.
- Increasing Hmet weight fraction reduces secondary component propellant volumes very strongly meanwhile the Hmet propellant volume increases moderately.
3.4.2 INFLUENCE OF PROPELLANT STORAGE TEMPERATURE

Metastable metallic hydrogen propellant could call for storage temperature down to 5 K. If the cryogenic propellant components LH2, SLH2 or SH2 are used, storage temperature still down to 12 K (for SH2) is required. The most serious tank design problems for cryogenic propellants reduces to the design of adequate thermal tank insulation. A simple approximation of the insulation thickness and specific density will answer the question, if storage temperatures in the mentioned ranges will be problematic.

The insulation requirements may be specified for the three phases listed in Tab. 3-5.

<table>
<thead>
<tr>
<th>Requiring phase</th>
<th>Objective</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground hold period</td>
<td>To reduce evaporative losses and radiative heat</td>
<td>Insulating blankets (removed prior to chill)</td>
</tr>
<tr>
<td>Boost phase</td>
<td>To reduce heat transfer due to conductive heating</td>
<td>e.g. aluminum-type insulation</td>
</tr>
<tr>
<td>Coast flight in space</td>
<td>To prevent propellant from radiation from sun and the planets</td>
<td>Radiation shield (temperate octave, silver applied as coating over light heat aluminum)</td>
</tr>
</tbody>
</table>

Tab.3-5: Insulation requirements for propellant tanks

From the mass of propellant tank point of view the ground hold period and boost phase are of importance. To investigate the latter point, the general steady-state heat-transfer equation has been used:

\[ q = \frac{Q}{A} = (k \cdot t) \cdot DT \]

where

- \( q \): Heat flux or heat, transferred per unit area per unit time [W/m²]
- \( Q/A \): Heat transferred per unit time [W] across a surface A [m²]
- \( t \): Chamber wall thickness [m]
- \( k \): Thermal conductivity of chamber wall [W/mK]
- \( DT \): Temp. differential across the insulation (T2-T1) [K]

Tab. 3-6 shows the regarded temperatures during the ground hold phase and the boost phase.

<table>
<thead>
<tr>
<th>T[K]</th>
<th>Ground hold phase</th>
<th>Boost phase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T2</td>
<td>T1</td>
</tr>
<tr>
<td>14</td>
<td>263</td>
<td>263</td>
</tr>
<tr>
<td>20</td>
<td>201</td>
<td>201</td>
</tr>
<tr>
<td>27</td>
<td>208</td>
<td>208</td>
</tr>
</tbody>
</table>

Tab. 3-6: Absolute temperatures and temperature differentials

As insulation a honeycomb light weight system has been chosen due to wide application for cryo-tanks. The cross section through the honeycomb-supported tank structure may be seen in Fig. 3-14. The insulation consists of a honeycomb core filled with foam (isocyanate-type), installed between an inner and outer facing laminate type sheet. The space of the gap between the tank wall and inner insulation surface is purged with helium to reduce the vacuum degradation by infiltration of air and to serve as leak-detection device. This insulation system delivers a thermal conductivity of about 2.88E-2 W/m°K (which is equivalent to 0.2 Btu-in/feet²°F).

Fig. 3-14: Construction element of a cryogenic tank insulation design (external type); [from 15]

The relative changes of thickness and density with storage temperature connected to the conventional liquid hydrogen system (T-storage: 20 K) is shown in Fig. 3-15. The approximated values are given for the ground hold and boost phase requirements.

Fig. 3-15: Approximation of per cent changes of the thickness and specific density of propellant tank insulation material for various propellant storage temperatures, connected to conventional liquid hydrogen storage conditions (20 K)

Results:

- Storage of propellants even at temperatures of about 5 K is technically feasible and will not increase the insulation masses dramatically
- Propellant storage temperatures in the range of slush hydrogen temperature (14 K) respectively solid hydrogen temperature (5 K) require an increase of insulation material thickness of about 2.25%/5.99 % for minimum values of ground hold phase respectively 0.87%/2.2% for boost phase conditions, compared
The propulsion concept design will primarily be the question of liquid propellant systems. The principles of liquid metallic hydrogen concepts are shown in Fig. 3-17 (p. 12). The feeding of the investigated propellants can be done by conventional methods, either by gas-pressure systems, turbopump systems or by combination feeding systems. A new feeding alternative of Hmet could be realized by electricity due to the conductive properties of Hmet. The required technology could be adopted e.g. from mass driver concepts. Magnetic fields moving down the Hmet propellant ducts acting as mass driver. Disadvantageous is the need of extra power required on board. It is conceivable, that, during the next millennium, energy transmission from the ground to the vehicle e.g. by laser beams could reduce this problem only to one of energy conversion. Some aspects concerning the different feeding systems are given:

- If metallic hydrogen is available at temperatures in the range of 5 K further research is necessary as to rotating parts of a turbopump system.
- Lower mass flows make the use of turbopump system easier.
- If lower percentages of Hmet are used (together with over proportional secondary mass requirements) a pressure feed system could be suitable for Hmet-feeding, a turbopump system for the secondary component.

3.5 PROPULSION CONCEPTS

The propulsion concept design will primarily be the question of tank arrangements, dependent on the state of aggregation of the propellants. Although the probability, that metallic hydrogen will exist in a solid state, a liquid system has also been investigated. A general review about the positive and negative characteristics of liquid, hybrid and solid hydrogen propulsion systems will be given below.

3.5.1 Liquid metallic hydrogen propulsion systems (Hmet/LH2, SLH2, RPI, MA)

The liquid systems are the propellant combinations PC1,2,3,4 from Tab. 3-2. Fig. 3-15 shows the overall propellant tank heights, based on a conventional bipropellant tandem arrangement. The maximum diameters have been defined to 6 m for the hydrogen tank and 3.8 m for the MA tank.

As may be seen from Fig. 3-15, the overall tank heights can be reduced dramatically with metallic hydrogen propulsion systems, compared to conventional launchers.

The principles of liquid metallic hydrogen propulsion concepts are shown in Fig. 3-17 (p. 12). The feeding of the investigated liquid propellants can be done by conventional methods, either by gas-pressure systems, turbopump systems or by combination feeding systems. A new feeding alternative of Hmet could be realized by electricity due to the conductive properties of Hmet. The required technology could be adopted e.g. from mass driver concepts. Magnetic fields moving down the Hmet propellant ducts acting as mass driver. Disadvantageous is the need of extra power required on board. It is conceivable, that, during the next millennium, energy transmission from the ground to the vehicle e.g. by laser beams could reduce this problem only to one of energy conversion. Some aspects concerning the different feeding systems are given:

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- Lower mass flows make the use of turbopump system easier.
- If lower percentages of Hmet are used (together with over proportional secondary mass requirements) a pressure feed system could be suitable for Hmet-feeding, a turbopump system for the secondary component.

3.5.2 Hybrid metallic hydrogen propulsion systems (SHmet-P, G/LH2, SLH2, RPI, MA)

The systems PC5 to PC12 (see Tab. 3-2, p. 4) use metallic hydrogen in solid form in conjunction with liquid working fuels. Metallic hydrogen in solid state is most likely. It can be classified as follows:

![Fig. 3-16: Different forms of solid metallic hydrogen](image)

SHmet could be stored as powder (microscopic particle size, SHmet-P) or as grain (macroscopic particle size, SHmet-G). The powder concept can be subdivided according to the number of required tanks into monopropellant and bipropellant systems. Monopropellant systems offer the chance to reduce the complexity of the overall storage system. Solid hydrogen could be used as suspension in direct combination with the secondary propellant component as slurry or gel. The latter is more viscous than a slurry propellant.

The conventional grain concept represents the classical solid grain, which is embedded inside the thrust chamber. Small pellets are stored in an extra tank. They will be inserted into the thrust chamber like the ammunition of a submachine gun. The rolling-up of solid metallic hydrogen wire represent another
grain concept.
Common to all solid concepts except suspensions, is the lower package respectively storage density due to air-spacing. However, this should be without prejudice for the overall system, if the fraction of metallic hydrogen is great enough, as mentioned in previous chapters. The different concepts are explained below. Most of them have been previously described for conventional metal combustion.

3.5.2.1 Powder bipropellant concept

This concept regards the solid hydrogen propellant as powder, which is stored isolated from the respective working fluid. It will further be distinguished between separate injection (concept A) and common injection (concept B) into the thrust chamber, as may be seen from Fig.3-17. The SHmet-P propellant will be fed by high pressure gas. The working fluid will be fed by a turbopump driven by a turbine, based on an open combustion tap off cycle.

In concept A the SHmet-P will be injected directly into the thrust chamber. Concept B introduces a mixing of the components before injection into the chamber. The mixing process is realized by means of the ejector principle. The main advantages and disadvantages of the two diegol concepts are summarized in Tab.3-7.

<table>
<thead>
<tr>
<th>Concept A</th>
<th>Concept B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advantages</strong></td>
<td><strong>Advantages</strong></td>
</tr>
<tr>
<td>High storage density</td>
<td>Easy controllable force of reaction</td>
</tr>
<tr>
<td>No mixing of fluids before injection</td>
<td>More simple ignition head injection</td>
</tr>
<tr>
<td><strong>Disadvantages</strong></td>
<td><strong>Disadvantages</strong></td>
</tr>
<tr>
<td>Needing of SHmet-P only by means of pressure gas</td>
<td>Dust accumulation in the tank due to humidity</td>
</tr>
<tr>
<td>Mean appearance in the tank due to humidity</td>
<td>Dust accumulation in the tank due to humidity</td>
</tr>
<tr>
<td>Danger of clogging in the ducts/valves</td>
<td>Complicated filter technique required</td>
</tr>
<tr>
<td>Sensitivity to pressure/temperature</td>
<td>Complicated filter technique required</td>
</tr>
<tr>
<td>No fuel available</td>
<td>No fuel available</td>
</tr>
<tr>
<td>Unfavorable SHmet-P tank form</td>
<td>Unfavorable SHmet-P tank form</td>
</tr>
<tr>
<td><strong>Problems</strong></td>
<td><strong>Problems</strong></td>
</tr>
<tr>
<td>Determination of optimal particle size</td>
<td>Determination of optimal particle size</td>
</tr>
<tr>
<td>Production of homogeneous particle size</td>
<td>Production of homogeneous particle size</td>
</tr>
<tr>
<td>Fading of SHmet-P</td>
<td>Production of homogeneous particle size</td>
</tr>
<tr>
<td>Flow behavior (wall influences)</td>
<td>Flow behavior (wall influences)</td>
</tr>
<tr>
<td>Valve technology</td>
<td>Valve technology</td>
</tr>
<tr>
<td>Monitoring instrumentation (flow, quantities and levels in tank)</td>
<td>Monitoring instrumentation (flow, quantities and levels in tank)</td>
</tr>
<tr>
<td>Thermal behavior due to particle friction</td>
<td>Thermal behavior due to particle friction</td>
</tr>
<tr>
<td>Ignition behavior</td>
<td>Ignition behavior</td>
</tr>
<tr>
<td>Combustion characteristics (droplet size, evaporation behavior, burning velocity)</td>
<td>Combustion characteristics (droplet size, evaporation behavior, burning velocity)</td>
</tr>
</tbody>
</table>

Tab.3-8: Comparison of SHmet-P-monopropellant concepts

3.5.2.2 Powder monopropellant concepts (slurry/gel)

A monopropellant system is a potential alternative to reduce the system complexity and therefore a good chance to reduce the space transportation costs. The problems of slurry combustion are described in literature [17]. Although these investigations concentrated on coal-oil slurry combustion, many aspects can be adopted for a metallic hydrogen slurry concept. Slurry means a suspension of solid particles inside the liquid working fluid.

A gel is a liquid containing a colloidal structural network that forms a continuous matrix and completely encloses the liquid phase. For comparison of both concepts, see Tab.3-8. Illustrations of the concepts can be seen in Fig.3-17.

<table>
<thead>
<tr>
<th>Slurry concept</th>
<th>Gel concept</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advantages</strong></td>
<td><strong>Advantages</strong></td>
</tr>
<tr>
<td>Reduction of overall system complexity</td>
<td>Reduction of overall system complexity</td>
</tr>
<tr>
<td>Reduced number of components</td>
<td>Reduced number of components</td>
</tr>
<tr>
<td>Small vehicle size</td>
<td>Small vehicle size</td>
</tr>
<tr>
<td>Research projects just under way</td>
<td>Research projects just under way</td>
</tr>
<tr>
<td>No mixing of fuels before injection</td>
<td>No propellant sloshing</td>
</tr>
<tr>
<td><strong>Disadvantages</strong></td>
<td><strong>Disadvantages</strong></td>
</tr>
<tr>
<td>Needing of SHmet-P propellant by means of pressure gas (for gel propellant)</td>
<td>Needing of SHmet-P propellant by means of pressure gas (for gel propellant)</td>
</tr>
<tr>
<td>Danger of clogging in the ducts/valves</td>
<td>Danger of clogging in the ducts/valves</td>
</tr>
<tr>
<td>Complicated filter technique required</td>
<td>Complicated filter technique required</td>
</tr>
<tr>
<td>Special pumps necessary due to high viscosity</td>
<td>Special pumps necessary due to high viscosity</td>
</tr>
<tr>
<td>Gases system required (if clogging)</td>
<td>Gases system required (if clogging)</td>
</tr>
<tr>
<td>Flow behavior dependent on temperature</td>
<td>Flow behavior dependent on temperature</td>
</tr>
<tr>
<td>Cost of chamber is problematic</td>
<td>Cost of chamber is problematic</td>
</tr>
<tr>
<td>High viscosity can be reduced by heating</td>
<td>High viscosity can be reduced by heating</td>
</tr>
<tr>
<td><strong>Problems</strong></td>
<td><strong>Problems</strong></td>
</tr>
<tr>
<td>Needing of SHmet-P propellant by means of pressure gas (for gel propellant)</td>
<td>Needing of SHmet-P propellant by means of pressure gas (for gel propellant)</td>
</tr>
<tr>
<td>Mechanical stabilization in the microgravity environment</td>
<td>Mechanical stabilization in the microgravity environment</td>
</tr>
<tr>
<td>Influence of liquid weight fraction on flow behavior</td>
<td>Influence of liquid weight fraction on flow behavior</td>
</tr>
<tr>
<td>Determination of optimal particle size</td>
<td>Determination of optimal particle size</td>
</tr>
<tr>
<td>Production of homogeneous particle size</td>
<td>Production of homogeneous particle size</td>
</tr>
<tr>
<td>Influence of particle weight distribution</td>
<td>Influence of particle weight distribution</td>
</tr>
<tr>
<td>Flow behavior</td>
<td>Flow behavior</td>
</tr>
<tr>
<td>Flow behavior (wall influences)</td>
<td>Flow behavior (wall influences)</td>
</tr>
<tr>
<td>Valve technology</td>
<td>Valve technology</td>
</tr>
<tr>
<td>Monitoring instrumentation (flow, quantities and levels in tank)</td>
<td>Monitoring instrumentation (flow, quantities and levels in tank)</td>
</tr>
<tr>
<td>Thermal behavior due to particle friction</td>
<td>Thermal behavior due to particle friction</td>
</tr>
<tr>
<td>Ignition behavior</td>
<td>Ignition behavior</td>
</tr>
<tr>
<td>Combustion characteristics (droplet size, evaporation behavior, burning velocity)</td>
<td>Combustion characteristics (droplet size, evaporation behavior, burning velocity)</td>
</tr>
</tbody>
</table>

Tab.3-7: Different aspects concerning SHmet-P-bipropellant concepts (A: separate propellant injection; B: common injection)

3.5.2.3 Hybrid grain concepts

Here macroscopic grains of Hmet are regarded. It is completely unknown how solid metallic hydrogen in concentration of 100% will interact with its environment. From solid atomic hydrogen imbedded inside a solid molecular hydrogen matrix, high regression velocities in the range of 2.1 m/s are known. For this study metallic hydrogen mass flows will be assumed to be in the range of today's magnitudes, possibly by means of additives.

In the case of the conventional grain concept solid metallic hydrogen propellant is contained within the combustion chamber, in which the liquid working fluid will be injected. A more detailed critical examination may be seen from Tab.3-9. The pellet concept means, that spherical pellets of Hmet will be injected into the thrust chamber. Disadvantageous is the lower propellant package density in the tank and fluctuation of the combustion, dependent on the injection rate. Advantageous is the flow rate controllability and engine shut down capability in case of emergency. Production could be easy due to the small size particles, delivered by the diamond anvil cell. The wire concept is a completely new one. Solid metallic hydrogen is spooled onto a coil which could be driven by electric energy or pressure gas. Full thrust controllability is given. Disadvantageous will be the lower propellant package density combined with additional mass for the coil and bearings.
as well as the difficult sealing of the feeding lines. Moreover, the solid propellant has to be pliable.

The different grain concepts are compared in Tab.3-9 while illustrations are shown in Fig.3-17.

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Pellets</th>
<th>Wire</th>
</tr>
</thead>
<tbody>
<tr>
<td>High propellant density</td>
<td>Fully thrust control</td>
<td>Fully thrust control</td>
</tr>
<tr>
<td>Decreased probability of mist rain</td>
<td>Decreased probability of mist rain</td>
<td>Decreased probability of mist rain</td>
</tr>
<tr>
<td>Less cooling problems of the chamber wall</td>
<td>Decreased problems</td>
<td>Decreased problems</td>
</tr>
<tr>
<td>Easy package density</td>
<td>Easy package density</td>
<td>Easy package density</td>
</tr>
<tr>
<td>Low cooling problems</td>
<td>Easy package density</td>
<td>Easy package density</td>
</tr>
<tr>
<td>Povarly thrust control</td>
<td>Large shot device</td>
<td>Large shot device</td>
</tr>
<tr>
<td>Gas production in serv</td>
<td>Mechanical feeding by pressure gas</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Disadvantages</th>
<th>Pellets</th>
<th>Wire</th>
</tr>
</thead>
<tbody>
<tr>
<td>High burning velocity</td>
<td>Package density dependent on wettability</td>
<td>Package density dependent on wettability</td>
</tr>
<tr>
<td>Adequate necessary to reduce burning velocity</td>
<td>Combustion fluctuation</td>
<td>Combustion fluctuation</td>
</tr>
<tr>
<td>No feeding of liquid particles by pressure gas</td>
<td>Slow reaction</td>
<td>Slow reaction</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Problems</th>
<th>Pellets</th>
<th>Wire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influence of electric and magnetic fields</td>
<td>Propellant distribution in chamber</td>
<td>Propellant distribution in chamber</td>
</tr>
<tr>
<td>Combustion behavior (stability, mismatch)</td>
<td>No of chamber</td>
<td>No of chamber</td>
</tr>
<tr>
<td>Combustion cut off</td>
<td>Optimum package size</td>
<td>Optimum package size</td>
</tr>
<tr>
<td>Influence of package size</td>
<td>Faster feeding rate</td>
<td>Faster feeding rate</td>
</tr>
<tr>
<td>Pressure feeding</td>
<td>Pressure feeding</td>
<td></td>
</tr>
</tbody>
</table>

Tab.3-9: Comparison of potential grain concepts

3.5.3 Solid metallic hydrogen propulsion system (SHmet-P/SH2)

A solid propellant metallic hydrogen propulsion system is conceivable as a solid hydrogen matrix, in which solid metallic hydrogen particles are inbeded. It makes more sense to use a microscopic powder rather than macroscopic solid particles because of the more homogeneous combustion behavior.

A concept like this offers the known conventional advantages, listed in Tab.3-10. They vanish immediately, if e.g. stability of solid particles can’t be assured in case of quarrlesomeness between SH2 and SHmet (e.g. due to different component temperatures or mechanical respectively thermal sensitivity). A simple illustration of the concept can be seen in Fig.3-17.

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>- No feed systems</td>
<td>- Difficult propellant production</td>
</tr>
<tr>
<td>- No valves</td>
<td>- Low storage temperatures</td>
</tr>
<tr>
<td>- Simple in construction</td>
<td>- Long duration storage problematic</td>
</tr>
<tr>
<td></td>
<td>- Cigarette-burner (-&gt;small burning area, changing chamber volume)</td>
</tr>
</tbody>
</table>

Problems |

- High temperature gradients through propellant cooling |
- Unknown combustion reaction velocity as function of chamber |

Tab.3-11: Analysis of solid propellant metallic hydrogen propulsion concept

Fig.3-17: Illustrations of possible metallic hydrogen propulsion concepts
3.6 PROPULSION PERFORMANCE

The following figure 3-18 gives the relations between metallic hydrogen percentage in the fuel and global vehicle mass fractions for the most advantageous propellant combination, Hmet/LH2. Of importance are payload mass ratio M1/M0, dry mass ratio M2/M0 and propellant mass ratio M8/M0 which gives total vehicle mass in the sum. The values given base on simple basic rocket equation calculation rather than on a detailed mass model. Launch masses required for reaching the velocity increment of 9300 m/s with constant vehicle dry mass of 30 Mg, are inserted into the columns for each calculation.

![Fig. 3-18: Approximations of the main vehicle mass ratios dependent on metallic hydrogen percentage and varying payload masses (SSTO-calulation)](image)

Results:
- Resulting vehicle launch masses for given mission demands are low, compared to existing launchers, even at low Hmet mass fraction.
- Payload mass ratios were kept constant for different payload masses.
- Use of metallic hydrogen propellant yields a great potential for launch mass reductions.
- Increase of dry mass ratio with %Hmet results from constant payload mass.
- At low metallic hydrogen weight fractions of 5%, with a payload mass of 5 Mg represent mass ratios of today's launchers (note: SSTO calculation with DV=9300 m/s).
- The propellant mass ratio decreases to a minimum of 50.4% with 100% metallic hydrogen.
- Payload mass ratios increase with payload mass for all combinations, while the dry mass ratios decline. Today, dry mass ratios in the range of 10% to 13% are feasible. All computed dry mass ratios above this range (see Fig.1) indicate free mass potentials which could be used either for higher payload masses or for heavier but more stable and therefore safer vehicle structures.
- Dry mass ratios for 200 Mg of payload are lower than 6.5% in each case, which indicates the need for better weight structures if payload mass is not to be reduced.

3.7 ENVIRONMENTAL ASPECTS

One dominant characteristics of super high energy metallic hydrogen propellant is the specific impulse. However there exists limits for the specific impulse primarily due to acoustics. The negative effects to the surroundings of the launch vehicle:
- Mechanical effects (e.g. on ground equipment by vibrations etc.)
- Chemical effects (e.g. on the atmosphere the vehicle is flying, through)
- Thermal effects (e.g. on the atmosphere or on the ground)
- Acoustical effects (on the surrounding but also on the vehicle itself)
- Emergency destruction effects (around the point of vehicle destruction)

Not all of these effects seem to be critical for the operation of the launch vehicle. The present paper discusses only the problematic effect, which arises due to the enormous exhaust velocities, dependent on metallic hydrogen weight fraction.

The primary impact comes from the sound, which is defined as mechanical oscillation inside an acoustic medium. It is measured as sound pressure and sound velocity. The oscillating pressure has the most dominant destructive influence on technical structures with resulting effects on the environment. Practically the sound pressure level $L_p$ is measured in decibel:

$$L_p [dB] = 10 \log_{10} \left( \frac{p^2}{P_{0}^2} \right)$$

where:
- $p$: Oscillating pressure

To quantify the effect of acoustic noise, the power of sound has been calculated. Between 0.7 and 1.6 the Mach emitted power of sound by a jet-stream is raising with eight to the power of the exhaust velocity $v$. With an exhaust velocity greater than mach two ($v > 2$ Mach), the jet-stream power of sound rises with 3 to the power of the exhaust velocity (27, p. 281). Fig. 3-19 shows the results of the parametric calculation of the acoustic noise level as function of the jet exhaust velocity with the distance $r$ from the source as parameter.

Sound levels over 200 dB are not at all acceptable for technical structures. It should be mentioned that values over 194 dB would be equivalent to an alternating pressure greater than 105 N/m²!

As limiting values for sound pressure level it may be proposed [19]:
- 145 dB as maximum stress limit for conventional rocket technical structures
- 160 dB as maximum stress for highly stable designed structures and launch facilities (submersible launch towers, concrete shelters for measuring tools etc.).

 Whereas from another authority [20] a maximum alternating sound pressure stress of 0.1 bar ($= 10^4$ N/m²) may be regarded
as tolerable. This limiting value is equivalent to a sound level of 174 dB. Future research activities at the Technical University of Berlin will include detailed investigations of the correlation between high exhaust velocities and generated noise power.

Fig. 3-19: Acoustic noise level as a function of exhaust jet velocity with distance r as parameter [19]

Results:
• Gas exhaust velocities above those of conventional systems (4500 m/s), enhance the maximum stresses of structures (r A only of vehicle) near destructive limits, due to increased noise levels.
• Metallic hydrogen weight fraction is an important parameter to be considered concerning acoustical effects.
• To take advantage of high energetic propulsion systems, methods concerning effective noise reduction (below 174 dB) have to be investigated.
• The only effective method in the moment to reduce the noise power, seems to be air augmentation.
• Vehicle mass savings (due to high propellant energetics) may probably be compensated partly by mechanical devices to realize air augmentation.

3.8 REFLECTIONS ON COSTS

The introduction of a new propulsion concept will be favoured, if there will be a potential for cost savings, namely for development and operation costs. In particular, the specific space transportation costs ($/kg-payload) respectively the vehicle launch costs are of importance. They can be reduced through high payload capabilities, high launch rates and low system complexity. Mostly, space system costs can be expressed as function of masses, as have been done in this study. It should be noted, that the following reflections are more general rather than based on detailed analysis.

As may be seen from Fig. 3-18 (chapter 3.6), the use of a Hmet/H2 propulsion system yields overall launch masses, much lower than today's launchers. Hmet vehicles yield furthermore higher payload capabilities with less system complexity. The low launch masses respectively the high launch mass ratios represent a possible potential to reduce the system costs. In Fig. 3-20, the approximated ranges of Hmet-vehicle launch costs are marked, based on a parametric comparison with past, todays and near future launchers.

Fig. 3-20: Approximation of launch costs of metallic hydrogen transportation systems, compared to various launchers [1]

Conclusions:
• Propellant combinations using more energetic working fluids (first hydrogen, second methyl alcohol, third RP1) yield lower launch masses and hence lower launch costs.
• Launch costs can be reduced with increasing metallic hydrogen weight fraction.
• Launch costs of Hmet-vehicles are much lower than conventional ones carrying the same payload mass.
• Areas for the Hmet-vehicles represent the upper limit of the expected launch costs, because that the mass values are based on SSTO calculations ($/kg-payload, systems are less complex compared to staded vehicles, and will therefore lead to reduced launch costs).

Fig. 3-21 shows the correlation between payload capability and specific costs ($/kg-payload). The approximated range for Hmet systems is marked. Space transportation based on metallic hydrogen system will be less costly, compared to conventional systems, due to much lower launch masses for the given payload masses.

Further reflections on costs of Hmet-systems are:
• The super high energetic propellant combination will require enhanced security demands which could lead to higher operational costs.
• Cost reduction potential due to less complex ground infrastructure (smaller propellant storage facilities, smaller hangars and launch towers, etc.)
• Design of reusable space vehicles using metallic hydrogen propellant systems could be advantageous due to smaller overall vehicle size.
• Use of hydrogen based Hmet combination could be much
cheaper than hydrocarbon combinations, due to probably spreading hydrogen house keeping world wide during the next millennium.

![Diagram](image)

**Fig.3-21: Approximation of specific transportation costs ($/kg) of metallic hydrogen transportation systems compared with conventional systems; data of given launchers have been converted into GTO data [1]**

**4. SUMMARY**

The study investigates metallic hydrogen for the application as rocket propellant. Due to its very high theoretical specific energy of 52 kcal/g, yielding a maximum specific impulse of 1700 m/s, and its high density of 1150 kg/m³, metallic hydrogen would be an interesting propellant candidate. However, there are many restrictions concerning the knowledge about metallic hydrogen:

- The required atomic state of Hmet has not yet been proven (required pressures for dissociation in the range between 2.5 and 4.0 Mbar have not been achieved today).
- Uncertainty about the metastability of metallic hydrogen (probably Hmet will not be metastable).
- Uncertainty about basic chemical and physical properties, like state of aggregation (probably Hmet will be a solid).

All investigations took place on condition that Hmet will exist in an atomic state and will be stable.

Different types of potential propulsion systems (liquid, hybrid and solid system) have been analysed. Three different propellant combinations have been compared: metallic hydrogen with hydrogen (liquid, slush and solid hydrogen) as working fluid, with RP1 and with methyl alcohol as working fluid. The main system parameter is the metallic hydrogen mass fraction, which influences the overall propulsion and vehicle performances primarily.

It may be seen from this study that metallic hydrogen is of advantage, compared to propellants used today. The overall vehicle masses enhance the complexity of possible Hmet launchers will decrease, due to increased propulsion performance. Nevertheless, gas exhaust velocities must not be increased unlimited, due to noise impact. For that reason, the Hmet propellant combination using LH2 as working fluid is of advantage, yielding improvements of system performances even with today's exhaust velocities.

The main results and conclusions followed the investigation of combustion characteristics, thrust chamber cooling, storage concepts, propulsion system performance, environmental loads and costs are summarized below:

- All system parameters depend largely on metallic hydrogen mass fraction.
- Combustion gas temperature is mainly dependent on metallic hydrogen mass fraction (up to 6000 K with high percentages; down to 1500 K for low percentages [conventional LOX/LH2 system :3750 K]).
- There are lower thermal risks of thrust chamber due to lower chamber temperatures, if metallic hydrogen propulsion is used delivering specific impulses of today's systems (low percentages of metallic hydrogen).
- An enormous increase in specific impulse arises, if chamber temperatures are not kept within conventional limits (combination using hydrogen as working fluid shows the most extreme behavior).
- The propellant systems Hmet/LH2 and Hmet/MA shows different behaviors concerning cooling requirements.
- Today's cooling technology is applicable up to 30% Hmet for system Hmet/LH2.
- Today's cooling technology is applicable only up to 5% Hmet for the system Hmet/MA.
- System Hmet/LH2 offers a great potential for cost savings in the fields of chamber and cooling technology.
- Enhanced commercial research towards increased thermal conductivity and low thermal expansion coefficients is required if high Hmet mass fractions are used.
- Metallic hydrogen weight fractions in the range of 40% will lead to increased payload mass ratios and reduced propellant mass ratios compared to conventional systems.
- Hydrogen as working fluid combined with Hmet represents the most interesting propellant alternative due to lowest overall vehicle masses.
- Highest payload mass potential with respect to realizable dry mass respectively structure mass ratios even at low Hmet weight fractions.
- High percentages of metallic hydrogen may lead to a dramatic decrease of overall propellant volume due to high density of Hmet (1.15 g/cm³).
- The most effective reductions in propellant volumes are achievable with methyl alcohol and RP1 as working fluids.
- Low temperature propellant storage (for typical prelaunch phases) at about 5 K could be achieved with conventional insulation techniques.
- Metastable liquid state of metallic hydrogen would be of advantage, compared to solid state, due to technical proven components (feeding system, valves, etc.).

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• If Hmet was metastable in solid state, a hybrid system would be advantageous, using Hmet as powder or in the shape of macroscopic pellets.
• Noise from rocket engines represent one of the most critical impacts to the environment.
• The advantage of high specific impulses will be compensated by the disadvantage of enhancement of the maximum stresses of structures near their destructive limits due to acoustic power.
• Methods concerning effective noise reduction (below the limit of 174 dB) have to be researched (air augmentation).
• Vehicle mass savings (due to high propellant energetic and hence low propellant masses) may be compensated partly by mechanical devices required for air augmentation.
• Propellant costs will depend on high pressure facility capabilities.
• There is a potential of launch costs and specific transportation costs savings due to the very low vehicle launch masses.
• There could exist a cost reduction potential due to less complex ground infrastructure (smaller propellant storage facilities, smaller ground launch facilities, etc.).
• Use of reusable SSTO space vehicles using metallic hydrogen propulsion systems will no longer be a problem.

Future research activities should concentrate on the following open technology problem areas:

• Development of high pressure facilities generating required pressures for Hmet production up to 4.0 Mbar.
• Detailed mass model, dependent on the storage concept.
• Detailed investigation of air augmentation techniques.

GENERAL MESSAGE:

• The use of metallic hydrogen as rocket propellant could lead to revolutionary changes in space vehicle philosophy towards low weight, small size and high performance SSTO systems.
• Hydrogen (liquid or slush) is the most favourable candidate as working fluid.
• Much more research in the field of high pressure physics is required to come to reliable statements about the chemical and physical properties of metallic hydrogen.
• The technical risks concerning the use of metallic hydrogen as rocket propellant may be controllable.

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