High Energy Density Matter for Rocket Propulsion

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The objective of the High Energy Density Matter (HEDM) program is to identify, develop, and exploit high energy atomic and molecular systems as energetic sources for rocket propulsion applications. It is a high risk, high payoff program that incorporates both basic and applied research, experimental and theoretical efforts, and science and engineering efforts. The HEDM program is co-sponsored by the Air Force Office of Scientific Research (AFOSR) and the Phillips Laboratory (PL/RKS). It includes both in-house and contracted University/Industry efforts. Technology developed by the HEDM program offers the opportunity for significant breakthroughs in propulsion system capabilities over the current state-of-the-art.

One area of great interest is the use of cryogenic solids to increase the density of the propellant and to act as a stable matrix for storage of energetic materials. No cryogenic solid propellant has ever been used in a rocket, and there remain engineering challenges to such a propellant. However, these solids would enable a wide class of highly energetic materials by providing an environment that is at very low temperatures and is a physical barrier to recombination or energy loss reactions. Previous to our experiments only hydrogen atoms had been isolated in solid hydrogen. To date we have succeeded in trapping B, Al, Li, N, and Mg atoms in solid H_2. Small molecules, such as B_2 and LiB, are also of interest. Current efforts involve the search for new energetic small molecules, increasing free radical concentrations up to 5 mole percent, and scale-up for propulsion testing.

High Energy Density Matter

- **Charter:** ***to beat*** $\boldsymbol{LH_2/LO_2}$
  - **Many energetic materials qualify**
  - **Most likely way by stabilizing HEDM within cryogenic solids.**
  - **Could result in four times payload-to-orbit for same size systems.**

- **Other significant gains can be made in improving both solid and liquid propellants**

The HEDM program consists of several working areas. The objective is to produce propellants that provide significant gains over existing propellants, including current solid rocket propellants, LOX/RP-1, and LOX/liquid hydrogen. The largest gains can result from inproving LOX/liquid hydrogen, which is the aim of the cryogenic solids working group. The two potential technology area for use of cryogenic solids as substitutes for LOX or liquid hydrogen are cryogenic solid hybrid rocket motors and cryogenic slurries consisting of solid hydrogen with entrapped HEDM additives as a slurry in liquid helium.

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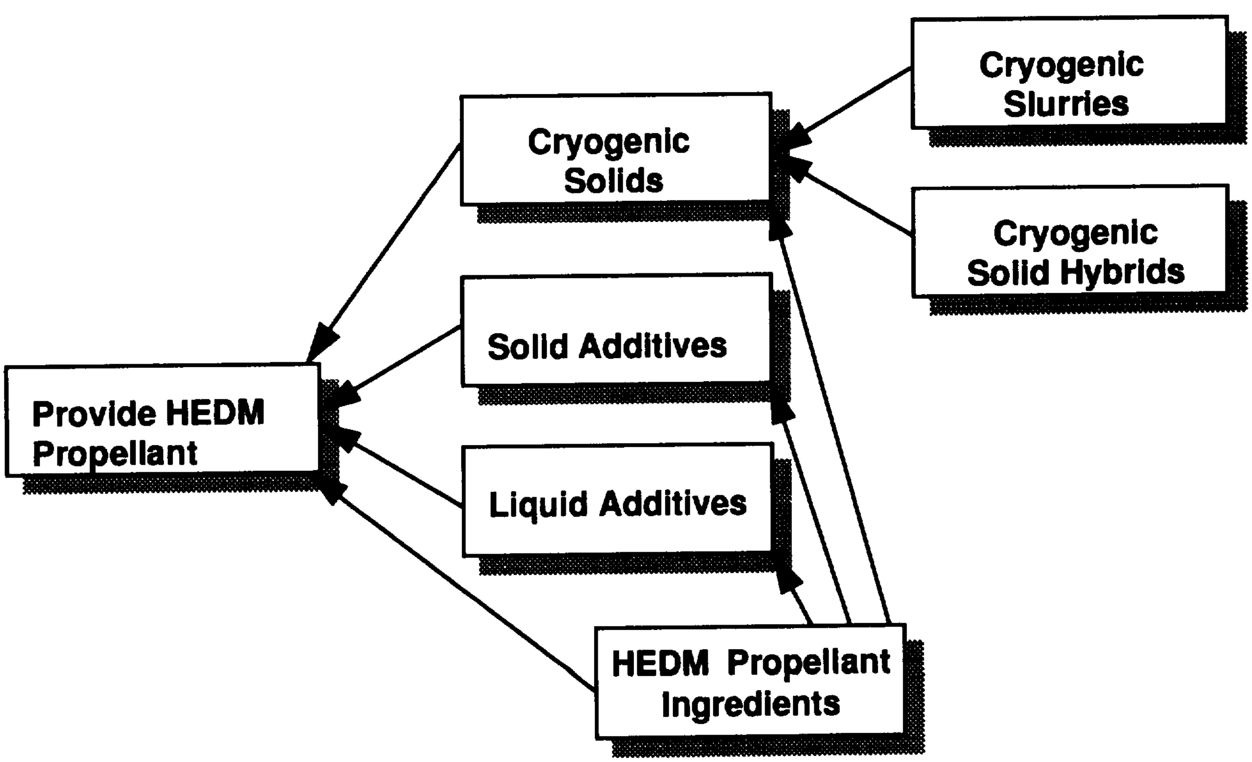

Propellants developed in the HEDM program range from near term application additived to LOX/RP-1 to very far term propellants, such as metallic hydrogen. One promising technology is in the area of cryogenic solid hybrid motors consisting of mixtures of energetic molecular systems, such as ozone, in "standard" propellants, such as oxygen. These mid-term technologies have the capability to provide 5 - 10 % improvements in specific impulse and density in the next 10 to 20 years.

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Technology Assessment: Advanced Propellants

Near Term	Mid Term	Far Term
Hydrocarbon additive to RP-1; advanced oxidizers and monopropellants (such as HAN, XM46)	Solid O_3/O_2 hybrid; Solid C_2H_2/H.C. hybrid; Advanced oxidizers (such as HADN, HNF)	Atoms in solid H_2 hybrid; HEDM/H_2/He slurry; Metallic hydrogen; Anti-matter, etc.

Approximate System Integration Targets

Near Term (5-10 years)	Mid Term (10-20 years)	Far Term (20-50 years)

Specific Impulse (sec) and Density Gains (%) over current like systems

Near Term	Mid Term	Far Term
5 - 15 seconds	10 - 25 seconds	20 - 100+ seconds
0 - 5 %	0 - 10 %	0 - 20 %

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The cryogenic solids technology area is focused on three main areas for propellant improvements: solid hydrogen, solid oxygen, and solid hydrocarbons. Simple density increases can be obtained in all three areas, but especially in solid hydrogen and solid oxygen. Significant specific impulse gains can be obtained with atomic and molecular additives in solid hydrogen. The solid hydrocarbon area is primarily for model system studies due to ease of use and safety. However, some gains in performance over LOX/RP-1 systems may also be realized by enabling the use of energetic hydrocarbons that cannot be used in conventional rocket systems.

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Cryogenic Solid HEDM Propellants

Develop Cryogenic Solid Materials Capable of Storing High Energy Density Additives

- **Solid Hydrogen**
  - **Densification of liquid H_2**
  - **Atomic or molecular additives**
  - **Scale-up**
  - **Handling and transport**

- **Solid Oxygen**
  - **Densification of liquid O_2**
  - **Ozone/other additives**
  - **Hybrid cryo. thruster**

- **Solid Hydrocarbons**
  - **Hybrid thruster under development**
  - **Easy to study model system for solid H_2 or O_2**
  - **Stable matrix for other energetic additives**

[redacted]

1. **Why are we interested in cryogenic solids for propellants?**

- **Greater Propellant Density**: % Increase
  - Liquid H_2 = 0.07 g/cc, solid H_2 = 0.087 g/cc **+ 24 %**
  - Liquid O_2 = 1.149 g/cc, solid O_2 = 1.55 g/cc **+ 35 %**

- **Can Store Energetic Additives**:
  - Atoms (H, Li, **B**, C, **N**, O, H, **Al**, Si) in solid H_2
  - Small molecules (B_2, **LiB**, BC, ...) in solid H_2
  - Ozone, O atoms, and other oxidizers in solid O_2

2. **What is the payoff for rocket propulsion?**

- Increased Specific Impulse*:
  - LOX/LH_2 = 390 sec, 5% B in H_2 = 472 sec **+ 21 %**
  - 50% **ozone** in solid oxygen = 410 sec **+ 5 %**

3. **How can we make rockets from cryo solid propellants?**

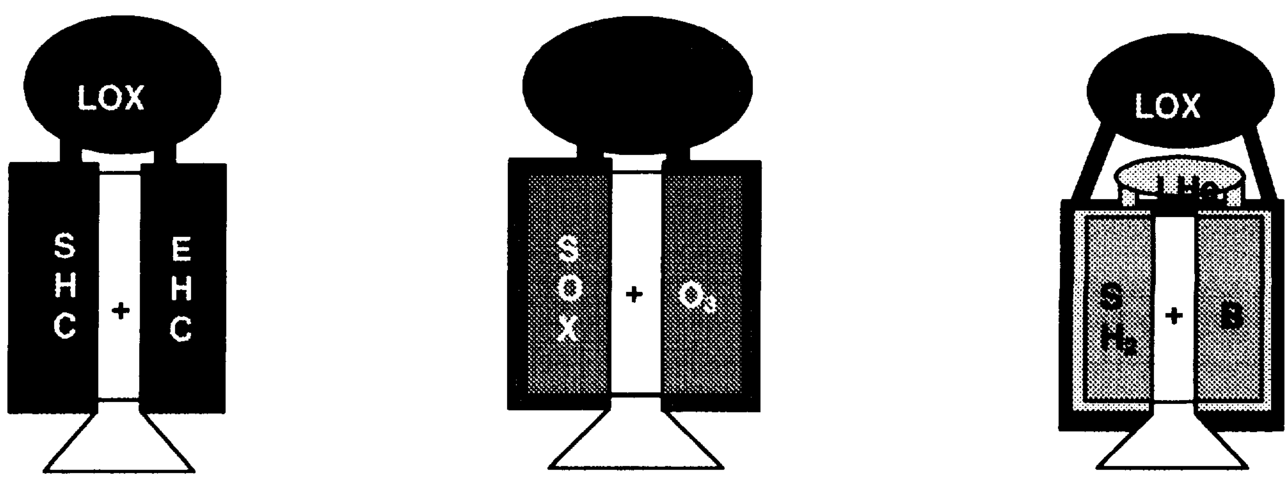
- **Cryogenic solid hybrid** design
- **Cryogenic slurry** of solid H_2 in liquid Helium

* ODE calculation of Specific Impulse at 1000 psi chamber pressure with expansion to 14.7 psi

The cryogenic solid hybrid motor research has made significant progress in the last year. The first step was to determine the feasibility of combustion of a cryogenic solid hydrocarbon stored at liquid nitrogen temperatures. The successful test firing of a lab-scale motor demonstrated the potential use of cryogenic solid propellants in a hybrid configuration. The recently accomplished first test of a "reverse" hybrid solid oxygenmotordemonstrates the feasibility of the use of oxygen/ozone mixtures in a hybrid design. The solid hydrogen/HEDM additives hybrid design is still untested.

Cryogenic Solids
Cryogenic Solid Hybrid Propellants

PHASE 1:	***PHASE 2:***	***PHASE 3:***
Short Term	**Mid Term**	**Far Term**



Currently Test Firing	**SBIR Program: Test Motor to be delivered Spring '96**	**One Focus of HEDM Basic Research**

The resent results of our 6.1(basic research) and 6.2 (exploratory development) work gives us reason to be optimistic about the chances of using advanced propellants for future rocket propulsion. We have yet to encounter any "show stoppers" in these technology areas. A great deal of research and development is necessary before any of these systems actually "fly", but the progress that has been made in the past few years indicate that the estimates for use of these technologies (shown on a previous slide) may be possible.

Results

- ***Solid ethylene at 77K was combusted with gaseous oxygen.*** **First time (that we know of) that a solid cryogenic fuel has been combusted in a controlled manner.**
- **Design for solid O_2 motor completed (SBIR, phase 2); testing started this month.** ***First successful combustion of solid oxygen with gaseous hydrogen.***
- ***Several atomic additives were successfully isolated in solid hydrogen*****; some energetic molecules were also observed.**
- **Solid H_2 / Superfluid Liquid He scale-up experiment built; recent testing of nitrogen atoms in solid nitrogen/helium.** ***First successful demonstration of transport of a HEDM solid from 4K to 300K environment.***

The largest gains in performance will certainly be obtained if it is possible to use atoms or molecules stored in solid hydrogen. A practical rocket system based on these future propellants may provide as much at four times the payload into orbit for the same size rocket system. However, the technical and cost problems are substantial. Gains in other advanced cryogenic solid propellants may be lower, but the technological problems associated with construction of practical rocket systems are not as great and, therefore, these technologies may provide the best chance of significant gains in the future.

Summary

- **Significant specific impulse gains (> 60 s) for atomic and molecular concentrations as low as 3 mole %**
- **Statistical model shows concentrations of > 3% are possible**
- **Packaged deposition (i.e. clusters) of atoms or molecules in hydrogen may give large gains in specific impulse (> 100 s)**
- **Atoms and small molecules have been trapped in solid Ar and solid Hydrogen**
- **Some larger molecular systems may also provide significant performance gains**
- **Scale-up to "rocket size" seems very possible; we are now working in this area**