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Technical Notes

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Hydrogen Peroxide as an Alternate Oxidizer for a Hybrid Rocket Booster

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Introduction

AT the present time, the propulsion industry is investigating the merits of hybrid rocket propulsion as an alternative to liquid rocket engines and solid rocket motors. Currently, liquid oxygen (LOX) has been identified as the oxidizer of choice by the propulsion community, while the use of high concentration (85–90%) hydrogen peroxide (HP) has received a decreased emphasis. In this Note, we attempt to characterize the differences between a LOX-based system with one utilizing HP as the oxidizer.

HP has seen applications in rockets dating back to the German V-2 missile developed in World War II (WWII).[1] In fact, HP was used extensively by Germany during WWII in at least seven different devices with over 10,000 applications without a single reported failure.[1] The largest quantities of high-concentration HP handled was 90,000 lbm of 80–85% HP to power submarines. Extensive use of HP by Germany during the 1940s led to an interest in the U.S. in the 1950s.[2–6] Polyethylene (PE) was investigated as a potential fuel by some researchers[5,6] due to its good performance and its tendency to autoignite in the presence of high-temperature decomposition products of HP.

In spite of the success of these studies, HP propellants did not receive a great deal of attention in the three decades following these benchmark efforts. Probable reasons for this lack of interest include the desire to find maximum performance propellants as well as a general downturn in interest of hybrid propulsion. In the current era in which we seek low-cost, environmentally sound propellants, HP deserves a renewed consideration. With these ideas in mind, we seek to compare the HP/PE system with a popular combination using LOX and hydroxyl-terminated polybutadiene (HTPB) as fuel. We should point out here that PE may in fact not be the optimal choice, but we have selected it based on the fact that there is a history of successful combustion using this fuel with HP. Under these assumptions, we seek to determine both design and operational advantages and disadvantages of the respective propellants in this Note.

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Design Considerations

Design considerations were evaluated by developing a computer code[7] capable of performing preliminary sizing calculations for both systems. While the resulting design code does not include a trajectory simulation, it does perform basic sizing calculations (using actual material characteristics) for all major components of a hybrid booster. The design philosophy involved sizing a hybrid booster capable of accomplishing a mission equivalent to that of the solid rocket booster utilized on the Titan 34D vehicle. To this end, each booster was sized to provide a 7728 f/s ideal velocity increment[7] to an equivalent payload of 219,000 lb with an assumed burning duration of 120 s. In addition, the hybrid boosters were sized to obtain the same 10.2 ft overall diameter as the T34D motor.

The assumed gas generator engine cycles for each of the two propellant combinations is highlighted in Fig. 1. For the HP/PE system we make use of the monopropellant characteristics of HP in a gas generator that contains a suitable catalyst material made of silver-plated nickel screens. The LOX/HTPB system requires a separate liquid propellant (assumed to be H_2O_2) with associated pressurant bottle (assumed to be helium) in order to generate hot gases to drive the turbine. Even though more desirable fuels such as RP-1 could be used in this application, they have a minor influence on the overall mass characteristics of the vehicle. Furthermore, a liquid fuel also increases pump complexity by mandating an intermediate seal purge. In both systems, we assume that the turbine exhaust is expanded through a separate nozzle and that its overall efficiency is 40%. The engine cycles in Fig. 1 also indicate the simplicity of the HP/PE system in providing oxidizer tank pressurization. In the HP/PE system, we utilize gas generator gases directly, whereas the LOX/HTPB system requires a heat exchanger to gasify LOX for the autogenous pressurization system.

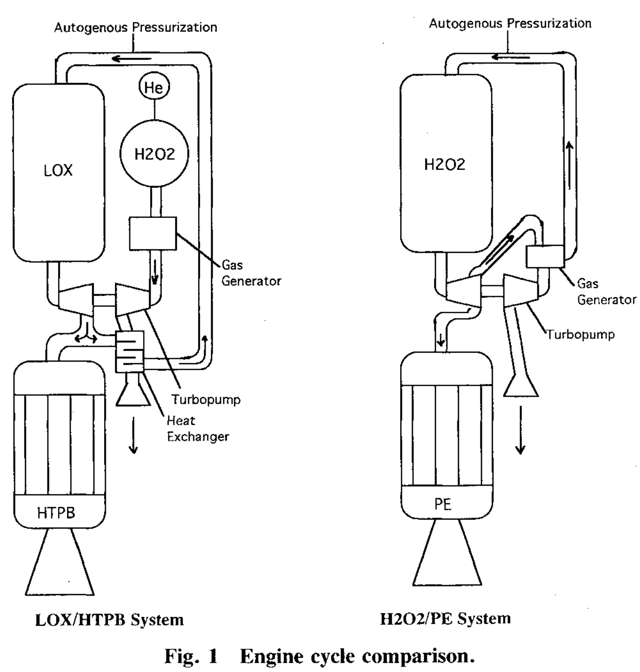

Fig. 1 Engine cycle comparison.

Weight models were developed for all of the major components (combustion chamber, nozzle, tank, intertank, turbopump, gas generator, pressurant bottles, etc.) of the systems. Chamber pressure optimizations were conducted for a fixed overall diameter. Results indicate that gross liftoff weight (GLOW) is quite insensitive to changes in chamber pressure near the optimal value for both systems and optimal values of 1100 and 1200 psi for the LOX/HTPB and HP/PE systems, respectively. The HP/PE system optimized at higher chamber pressure by virtue of the fact that the fuel section is smaller for this propellant combination. Both systems optimized at pressures slightly higher than is typical of solid rocket motors for a similar reason; only a fraction of the propellant lies in the combustion chamber.

Results of the studies at the chamber pressures selected above are presented in Tables 1–3 and Fig. 2. Table 1 provides a performance comparison between the two designs. Quoted I_{sp} values are at an altitude of 50,000 ft and reflect assumed efficiencies as described above. Since the HP/PE system has lower I_{sp}, higher thrust and mass-flow levels are required. Note that the HP/PE system enjoys a bulk density advantage of over 23% over the LOX/HTPB option due mainly to the density advantage of HP over LOX (87.4 vs 71.1 lb/f^3). The booster thrust-to-weight ratio was near 2 for both propellant combinations. This is also near the value for the T34D solid rocket motor, which indicates that these would be reasonable designs for possible replacement of this motor.

Table 1 Performance comparison, LOX/HTPB vs HP/PE

Item	LOX/HTPB	HP/PE
Chamber pressure, psi	1100	1200
Ullage pressure, psi	71.7	63.1
Oxygen flowrate, lb/s	1736	2382
Delivered engine, I_{sp}, s	311.2	280.6
Delivered vehicle, I_{sp}, s	309.6	279.5
Expansion ratio	16.5	17.8
Burning time, s	120	120
Booster F/W ratio	2.34	2.19
Bulk density, lb/f^3	66.2	81.6
Mixture ratio	2.5	7.5

Table 2 Dimensional comparison, in inches

Item	LOX/HTPB	HP/PE
Overall length	1100	976
Overall diameter	122	122
Chamber length	391	197
Chamber thickness	1.13	1.23
Tank length	549	610
Tank thickness, cylinder	0.172	0.190
Nozzle throat diameter	21.2	21.4
Nozzle exit diameter	86.3	90.5
Pump impeller diameter	8.76	9.52

Table 3 Weight comparison, in pounds

Component	LOX/HTPB	HP/PE
Usable propellant	294,247	327,241
Residual propellant	12,523	6,702
Oxygen tank pressurant	1,545	946
Oxidizer tank	4,044	4,918
Intertank	940	1,109
Combustion chamber	9,111	4,918
Nozzle (includes TVC)	2,080	2,237
Turbopump	173	222
Gas generator propellant	2,670	3,310
Gas generator	18	22
Main oxidizer valve	19	26
Heat exchanger	974	0
Pressurization line	95	84
Gas generator HP tank	72	0
Gas generator He + tank	194	0
Total inert weight	17,648	13,536
Booster mass fraction	0.898	0.932

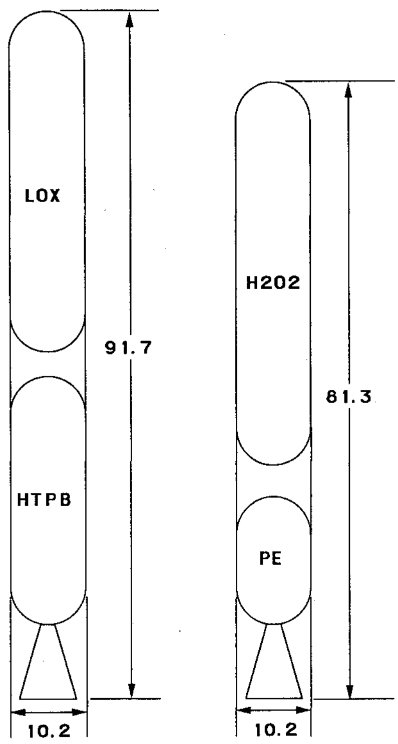

Fig. 2 Overall booster envelope comparison (all dimensions in feet).

A dimensional comparison of the two designs is shown in Table 2. In this case, the high mixture ratio operation in the HP/PE system leads to a larger oxidizer tank and smaller fuel chamber as compared to LOX/HTPB. Recall that tank and fuel section lengths were set by an overall diameter requirement of 10.2 ft. The envelope implied by overall length and diameters indicates that the HP/PE booster is 11% shorter than the LOX/HTPB design as shown in Fig. 2. This result is due to the higher bulk density and overall simplicity of the HP/PE system. The increased fraction of oxidizer in the HP/PE system also leads to a larger pump as evidenced by the impeller diameter comparison in Table 2.

A comparison of component weights for the two systems is presented in Table 3. High mixture ratio operation of the HP/PE system is responsible for decreased chamber and propellant residual weights as compared to the LOX/HTPB system. Note that no heat exchanger or gas generator propellant tank is required for the HP/PE system, and that the overall inert mass is less than that of the LOX/HTPB system. This point is important since vehicle fabrication costs are most strongly related to inert weight since propellant cost is not normally a major factor in systems of this type.

Finally, we note that mass fractions quoted in Table 3 do not include propellant residuals or any vehicle-related hardware (nosecone, separation and destruct system, external insulation, etc.), and have not included structural mass for attachment to the core vehicle. While these masses can be significant (they amount to more than 10,000 lb in current T34D booster), they will be similar for both the LOX/HTPB and HP/PE systems. For this reason, the mass comparison in Table 3 addresses the primary differences between the two systems.

Results of the design study indicate that the HP/PE booster is competitive in comparison to the LOX/HTPB system. The increased energy advantages associated with LOX are diminished not only by complexities introduced by this choice, but also by the fact that large fuel sections are required for optimal performance. For these reasons, there is no tremendous performance advantage in selecting LOX as the oxidizer.

Operational Considerations

Launch vehicle cost and schedules are primarily driven by operations. In fact, operations composed 75% of the total U.S. Space Launch costs in 1985.[8] While operations costs are lower for an expendable vehicle, they can still dominate costs even in this case. Simplicity of operations must be given more emphasis in today's environment, which emphasizes overall cost as an important design measure.

The HP/PE engine will capitalize on the monopropellant nature of HP to significantly reduce complexity (and associated operations) in comparison to the LOX/HTPB engine. The HP/PE engine will also offer the advantage of storability, which will reduce the system complexities introduced by cryogenic oxygen. A large part of booster operations costs are attributed to mechanical integration/mating of the vehicle. The HP/PE system has a much lower dry weight (inert weight plus fuel) than does the LOX/HTPB system and should be much easier to mate and stack. Results of our design study in the previous section indicate that the dry weight of the HP/PE system is roughly half that of the LOX/HTPB system. In addition, the HP/PE engine will reduce the number of required fluids, reduce the number of components, and eliminate difficulties associated with loading and launching a cryogenic system. A comparison of the fluid schematics for the two propellant systems is shown to highlight the simplicity of the HP/PE engine.

The propulsion system is a leading candidate for operations reduction. The operational efficient propulsion system study (OEPSS) report[9-11] was used to develop a comparative data base for the expected processing tasks for a strap on LOX/HTPB and HP/PE booster. The Lockheed Space Operations Company (LSOC) reduced the operations required to process a liquid rocket booster into major tasks called operations and maintenance instructions (OMI). The OMI tasks were reviewed and tailored to predict the cost to process a LOX/HTPB and HP/PE booster. While it is difficult to quantify the overall savings, this review definitely predicted that the HP/PE booster would be cheaper to process.

The OEPSS report also identified 25 concerns to improve safety or processing of the propulsion system. The HP/PE engine was comparable or superior to LOX/HTPB for all of the OEPSS concerns. In particular, the HP/PE engine was superior to the LOX/HTPB engine with respect to the fluid umbilical plate design, and cryogenic loads transmitted by the booster to the core vehicle.

Assuming that both vehicles use a fly-away umbilical, the LOX vehicle will require a LOX quick disconnect to replenish LOX flow during loading. The HP vehicle tank could be loaded with propellant and closed out without the need for any fluid umbilical. This would significantly reduce the hazards and complexity of a cryogenic quick disconnect umbilical as well as simplify the loading and launch of the vehicle. A LOX-based booster will undergo cryogenic shrinkage during loading, which will impose loads on the booster as well as the core vehicle. The HP/PE engine will naturally not have cryogenic shrinkage loads.

The HP system can be wet-leak checked with water, whereas the LOX system will require liquid nitrogen (LN2) or LOX. A wet-leak check with water instead of LOX or LN2 should be superior in terms of fluid cost, handling, and safety. Components in a HP system can be thoroughly tested with water, whereas LOX systems ultimately require cryogenic tests. Cryogenic testing, whether operational or development in nature, is more hazardous and difficult to perform than water testing.

As an example, the water flow testing on the Space Shuttle 17-in. disconnect valve was significantly cheaper and quicker than the cryogenic testing.[12] The approximate facility startup costs were three times higher for cryogenics vs water, and water flow tests were conducted approximately eight times faster than cryogenic testing. Cryogenic testing consumed approximately 80% of the total program test budget. Significant reductions in cost and schedule could be realized if water is used for HP component and system testing. Virtually all of the HP devices used during WWII were only water-flow tested before being deployed.[1]

For these reasons, the HP/PE engine is superior to a LOX-based engine with respect to vehicle processing and operations.

Fluid Safety Hazards and Handling

HP is a strong liquid oxidizer, and like other liquid oxidizers (including LOX), it is highly reactive with many substances. However, there appear to be two basic misconceptions regarding the behavior of HP. These misconceptions presume that HP is hazardous to handle and that it is highly unstable and can decompose or detonate. The authors have worked with 86–90% HP and have reviewed the literature extensively[13-17] to identify potential hazards. HP is comparable to LOX for fire, explosive hazards, and handling. The fluids have different characteristics, but if the same level of safety and care is applied to both fluids, similar levels of safety can be maintained.

HP is an oxidizer, and like other oxidizers it is highly reactive with a range of compounds. Pure or stabilized HP that is less than 95% in concentration, is not impact sensitive and cannot detonate unpredictably. This has been independently demonstrated with numerous tests.[1,13,16,18] Gaseous HP can ignite or detonate when the molar concentration is greater than 26%. It should be noted that if an HP vapor detonation does occur, the detonation does not propagate into the fluid. Therefore, the energy released in the detonation is limited to the available energy in the vaporized HP. In addition, the inherently low vapor pressure of HP makes it easy to avoid this condition during propellant handling operations.

Gross contamination of HP with catalytic agents or fuels can create mixtures that are explosive. A decomposition hazard can occur from contamination of the HP with catalytic agents, and in particular metal oxides. HP can also create a flammability hazard if it is spilled on cloth or wood that is contaminated with a catalyst. All HP is chemically stabilized to neutralize low levels of contamination, but like any oxidizer, HP cannot be stabilized against gross contamination. Typically, HP contamination can be detected as a temperature rise in a storage vessel and operational measures such as emergency stabilization or fluid dilution can mitigate fire and explosion hazards.

In contrast, LOX contamination will typically go unnoticed until the contamination creates a fire. The unpredictable hazard of LOX contamination fires was clearly shown when the Space Shuttle GOX flow control valves ignited and burned during component testing from particle impact fires.[19] Particulate contamination has been found in the Space Shuttle main propulsion system which could have initiated a fire in the flow control valves. Extensive component redesign of the flow control valves and system testing was required to reduce the GOX fire contamination hazard.

At ambient temperatures, the very low vapor pressure of HP allows personnel to handle the fluid without respiratory protection. HP compatible clothing must be worn to protect against personnel contact with the fluid, however, the type and amount of personnel protection is virtually identical to that required to handle LOX. HP that contacts skin will cause temporary bleaching, a stinging sensation, and possibly blisters. For a similar exposure, LOX will cause cryogenic burns. Therefore, we conclude that HP has comparable handling hazards to LOX.

Both HP and LOX are strong liquid oxidizers, which implies that care must be exercised in handling both substances. The hazards of LOX and HP are similar in their severity and comparable in the level of detail required for safe usage. The hazards of HP do not warrant a preference for LOX.

Conclusions

In this Note, we have compared both the design and operational characteristics of hybrid boosters using the HP/PE and LOX/HTPB propellant combinations. Results of our design study indicate that the HP/PE vehicle is of comparable size and inert weight as the LOX/HTPB system. Primary reasons for this result stem from the inherent simplicity of the HP/PE vehicle and the fact that this system operates at high mixture ratio, thus enabling reduction in fuel chamber and fuel residual mass. In addition, the bulk density advantage enjoyed by the HP/PE system enables a more efficient packaging.

Results of a study of operational characteristics indicate that HP is comparable in both safety and handling risks to LOX. Since the HP/PE engine is inherently simpler in design, we have found that it is also an inherently simpler vehicle to both process and launch. The particular nature of HP offers unique opportunities in system operations, such as auxiliary monopropellant usage, simpler wet leak check capability, and storable propellant operations. The distinct advantages of HP system make it a viable alternative to LOX for an economical strap-on booster.

References

[1]Walter, H., "Experience with the Application of Hydrogen Peroxide for Production of Power," *Jet Propulsion*, Vol. 24, No. 3, 1954, pp. 166–170.

[2]Bloom, R., Davis, N. S., and Levine, S. D., "Hydrogen Peroxide as Propellant," *Journal of the American Rocket Society*, No. 80, March 1950, pp. 3–17.

[3]Andrews, E. G. D., and Mottran, A. W. T., "Trends in the Development of Liquid Propellant Rocket Engines," *Aeronautical Quarterly*, Vol. X, Aug. 1959, pp. 199–210.

[4]Sanz, M. C., "Five-Pound Thrust Liquid Mono-Propellant Rocket," *Journal of the American Rocket Society*, Vol. 25, Sept.–Dec. 1948, pp. 122–125.

[5]Moore, G. E., and Berman, K., "A Solid-Liquid Rocket Propulsion System," *Jet Propulsion*, Nov. 1956, pp. 965–968.

[6]Pugibet, M., and Moutet, H., "Hydrogen Peroxide as an Oxidizer for Hybrid Rocket Engines," NASA TT-F-13034, 1970, p. 2854.

[7]Ventura, M. C., and Heister, S. D., "Hydrogen Peroxide as an Alternative Oxidizer for a Hybrid Rocket Booster," AIAA Paper 93-2411, June 1993.

[8]National Center for Advanced Technologies, "National Rocket Propulsion Strategic Plan," Aerospace Industries Association, Aug. 1990, p. 7.

[9]Byrd, R. J., "Operationally Efficient Propulsion System Study (OEPSS) Data Book, Vol. I—Generic Ground Operations Data," Rocketdyne, Canoga Park, CA, April 14, 1990.

[10]Waldrop, G. S., "Operational Efficient Propulsion System Study (OEPSS) Data Book, Vol. II—Ground Operation Problems," Rocketdyne, Canoga Park, CA, April 24, 1990.

[11]Wong, G. S., "Operational Efficient Propulsion System Study (OEPSS) Data Book, Executive Summary," Rocketdyne, Canoga Park, CA, April 24, 1990.

[12]Guerrero, J., personal communication, Rockwell International Space Systems Div., Downey, CA, June 1993.

[13]Bloom, R., and Brunsvold, N. J., "Anhydrous Hydrogen Peroxide as a Propellant," *Chemical Engineering Progress*, Vol. 53, No. 11, 1957, pp. 541–547.

[14]"Hazards of Chemical Rockets and Propellants Handbook," Vol. I, General Safety Engineering Design Criteria, NTIS, U.S. Dept. of Commerce, Springfield, VA, May 1972.

[15]"Hazards of Chemical Rockets and Propellants Handbook," Vol. III, Liquid Propellant Handling, Storage, and Transportation, NTIS, U.S. Dept. of Commerce, Springfield, VA, May 1972.

[16]"Hydrogen Peroxide Handbook," Chemical and Material Sciences Dept., Rocketdyne, North American Aviation, Canoga Park, CA, AFRPL-TR-67-144, July 1967.

[17]Krop, Stephen, "The Toxicity and Health Hazards of Rocket Propellants," *Jet Propulsion*, Vol. 24, No. 4, 1954, pp. 223–236.

[18]Schumb, W. C., Sanefield, C. N., and Wentworth, R. L., *Hydrogen Peroxide*, Reinhold, New York, 1955.

[19]"Metals Ignition Study in Gaseous Oxygen (Particle Impact Technique Relating to the Shuttle Main Propulsion System Oxygen Flow Control Valve Tests)," NASA TR-277-001, Johnson Space Center, White Sands Test Facility, 1982.

Effects of the Chemical Reaction Model on Calculations of Supersonic Combustion Flows

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Introduction

NUMERICAL modeling of reacting supersonic flow in a generic configuration at low enthalpy showed a strong effect of the selection of the reaction model on the solution. The calculation simulated an experiment in which one transverse injector of 1.5 mm diam was located three step heights downstream of a rearward-facing step (the step height is 5 mm). The air inlet conditions were 800 K, a static pressure of $\frac{1}{3}$ atm at Mach 2, with the fuel (gaseous hydrogen) injected at a total temperature of 300 K as an underexpanded jet with a sonic exit. The dynamic pressure ratio of hydrogen-to-air at inlet conditions was 1.5, and the total pressures were 567 and 395 kPa for hydrogen and air, respectively. The resulting overall equivalence ratio was 0.058. The length of the simulated domain was restricted to 4.4 cm (approximately eight step heights downstream of the step) to keep the intensive computational effort at a reasonable level. A mixing, nonreacting calculation was performed to provide a comparison with the reacting case. It required 15 CPU hours, whereas the reacting solution took 33 h to achieve convergence using a Cray-2S. This is effective computer time, which took advantage of the solution technique adopted that artificially accelerated the reactions.

Computational Model

The calculation used the three-dimensional version of SPARK. This code has been used previously in studies of reacting and nonreacting shear layers[1] and in conjunction with combustor experiments, with application to supersonic combustion of hydrogen injected tangentially into a supersonic airstream.[2] Validation studies of mixing were performed for flowfields generated by transverse injection in a Mach 2 stream.[3,4] These works included the evaluation of selected computational techniques, grid resolution, and several algebraic turbulence models. The objective of this work was to test the effects of the chemistry model for low enthalpy supersonic combustion.

The numerical model employs an elliptic three-dimensional Navier-Stokes solver and simulates turbulence based on the

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