A Single Stage to Orbit Rocket with Non-Cryogenic Propellants

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It is possible to design a practical single stage to orbit rocket with non-cryogenic propellants provided they are sufficiently dense. Several propellant combinations were compared to that of oxygen/hydrogen: nitrogen tetroxide/hydrazine, oxygen/methane, oxygen/propane, oxygen/RP-1, solid core nuclear/hydrogen, and hydrogen peroxide/JP-5. Of these, hydrogen peroxide and JP-5, a high-density jet fuel, offers 1.79 times the payload specific energy of oxygen and hydrogen. The specific impulse of H_2O_2/JP-5 is 335 seconds when burned at a mixture ratio of 7.35:1 and the bulk density of the propellants at 300 K is 1330 kg/m^3. Detailed thermochemical calculations were performed to substantiate this assumption, involving a rocket operating with an expansion ratio of 180 in vacuum. A detailed design for an oxygen/hydrogen-fuelled single stage to orbit vehicle was reaccomplished assuming hydrogen peroxide and JP-5 were the propellants. The component weights were classified as volume dependent (tanks, e.g.), surface area dependent (fuselage), height dependent (wiring), dry weight dependent (landing gear) and gross weight dependent (engines and engine mount). A Newtonian iteration was performed to determine the dry weight of the hydrogen peroxide/JP-5 vehicle, which was 29% less than the dry weight of the oxygen/hydrogen vehicle. There are operational advantages to using hydrogen peroxide and JP-5. The propellants are both liquids at room temperature. Hydrogen peroxide is relatively inexpensive, available in high purity, and compatible with a wide variety of materials. By catalytically decomposing the hydrogen peroxide to steam and oxygen before injection into the thrust chamber, the JP-5 can be injected as a liquid into a high temperature gas flow. This would yield superior combustion stability and permit easy throttling of the engine by adjusting the amount of JP-5 in the mixture. Development of modern hydrogen peroxide/JP-5 engines, combined with modern structural technology, could lead to a simple, robust, and versatile single stage to orbit capability.

Introduction

The empty mass M_e of a rocket is the sum of the weights of the individual components:

$$M_e = M_{pl} + M_t + M_s + M_{eng} + M_{tps} + M_{misc} \qquad (1)$$

where M_{pl} is the mass of the payload, M_t is the mass of the propellant tanks, M_s is the mass of the structure exclusive of tankage, M_{eng} is the mass of the engines, M_{tps} is the mass of the thermal protection system, and M_{misc} is the miscellaneous mass. The empty mass is related to the gross mass M_o by the relation:

$$\begin{aligned} M_o &= M_e\, r \\ &= M_e\, e^{\frac{\Delta v}{c}} \end{aligned} \qquad (2)$$

in which the required mission velocity change is indicated by Δv and the effective exhaust velocity is indicated by c. For the single stage to orbit mission, we take the value of mission velocity change to be 9,300 m/s, or 30,500 ft/s. The effective exhaust velocity, which is principally a function of the choice of fuel and oxidizer, is related to the more familiar specific impulse I_{sp} by $c = I_{sp}\, g$, where g is the acceleration of gravity at earth's surface, and appears in the equation only to convert the units from time to velocity. The number r is called the mass ratio, and is exponentially sensitive to changes in specific impulse.[1] It is also helpful to note that the mass of propellant, M_p, is the difference between the gross and empty masses, and hence that

$$\begin{aligned} M_p &= M_o - M_e \\ &= M_e(r - 1) \end{aligned} \qquad (3)$$

To illustrate the important effect of propellant density on overall rocket performance, consider the case where the mass of everything but the tanks is ignored. Equation 1 becomes:

$$M_e = M_{pl} + M_t \qquad (4)$$

We can rewrite this by defining a new term ε as the ratio of the mass of the tank to the mass of the propellant inside the tank. With this substitution, equation 4 becomes:

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$$
\begin{aligned}
M_e &= M_{pl} + \varepsilon M_p \\
&= M_{pl} + \varepsilon(r - 1)M_e \\
&= \frac{M_{pl}}{1-\varepsilon(r - 1)}
\end{aligned}
\qquad (5)
$$

So, for any propellant combination, if the value of $\varepsilon(r - 1)$ is greater than 1, the mission cannot be performed.

Conventionally, ε is taken to be a function of the overall level of structural technology used in the design. This is an oversimplification, however, because of the important effects of propellant density. Consider the simplest case, a spherical tank. The dominant load in a propellant tank is imposed by the pressure P_o at which the tank operates. The walls are constrained to a maximum operating stress σ, and are made of a material which has a density ρ_t. The liquid inside the tank has a density ρ_l. From these facts it is a straightforward calculation to show that:

$$
\varepsilon = \frac{3P_o\rho_t}{2\sigma\rho_l} \qquad (6)
$$

If we consider the performance of liquid hydrogen and liquid oxygen as a baseline, then figure 1 indicates the curve on which a change in density precisely balances a corresponding opposite change in specific impulse. Any propellant combination with a specific impulse and density that falls above the line is likely to lead to a vehicle with a lower empty mass for a given payload mass, and those falling below the line are likely to lead to correspondingly heavier vehicles.

It is more precise to adopt a formulation of equation 5 which includes the other components in equation 1. In general, one can classify components to whatever level of detail is required, and then determine which of them scale with propellant volume, gross mass, empty mass, surface area, linear dimension, or are invariant. A value of payload weight divided by empty weight can be obtained for any combination of propellant density and specific impulse.

It is clear from the preceding discussion that specific impulse is not necessarily the best figure of merit to use when assessing propellants for the single stage to orbit mission. The mission goal is to impart kinetic energy to a payload. The designer must provide propellants and the hardware to manage their storage and combustion. Accordingly, we define a new figure of merit, *payload specific energy*, e_{pl}, for assessing propellant utility as follows:

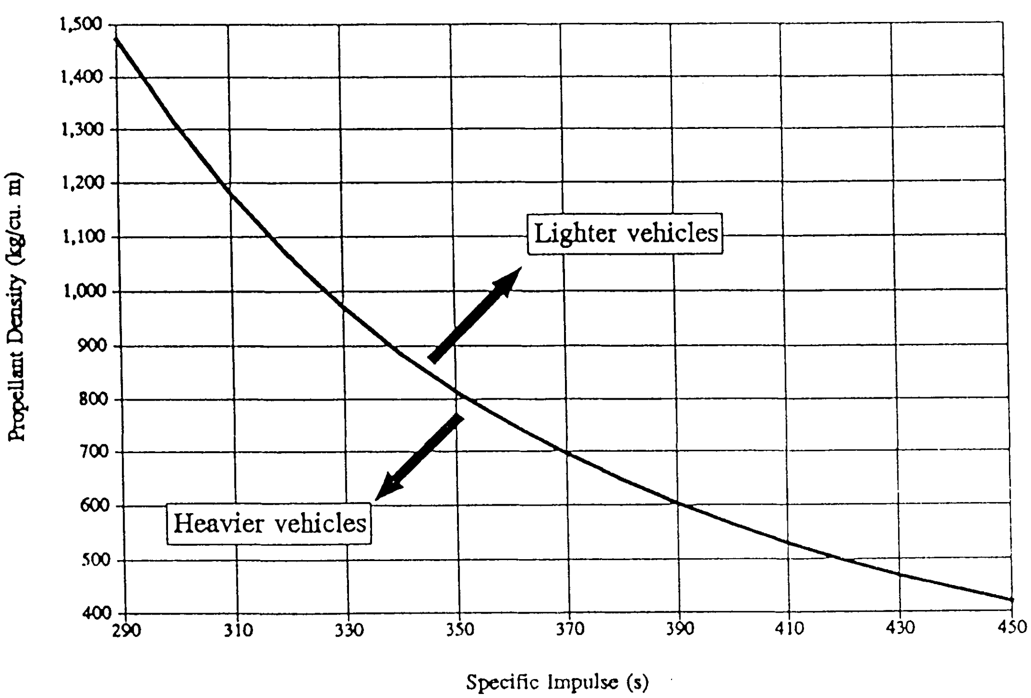

Figure 1: Tradeoffs between density and specific impulse

$$
\begin{aligned}
e_{pl} &= \frac{M_{pl}}{M_e}\eta_p \\
&= \frac{M_{pl}}{M_e}\frac{\textit{kinetic energy of empty mass}}{\textit{kinetic energy of jet}} \qquad (7)\\
&= \frac{M_{pl}}{M_e}\frac{(\Delta v/c)^2}{r-1}
\end{aligned}
$$

The expression for propulsive efficiency is the same as that used in Tsiolkovskij's 1903 book *The Exploration of the Universe with Reaction Flying Machines.*[2]

Several possible propellant combinations were assessed, using detailed scaling of the payload to empty mass ratios as discussed in the previous paragraph. The results are given below in figure 2. It is interesting to note that nearly any propellant combination is superior in this figure of merit to Oxygen/Hydrogen, which is conventionally assumed to be the only choice. The best propellant combination appears, based on this analysis, to be hydrogen peroxide and JP-5, a common military jet fuel with relatively high density. Because both of these propellants are cheap and liquid at room temperature, a closer look is in order.

History of Hydrogen Peroxide as a Rocket Oxidizer

Hydrogen peroxide, H_2O_2, was discovered in 1818[3] and has been used commercially as a bleaching agent, particularly for wool, for over a century. Its use as a propellant dates back to World War II, when it was used to power the Me-163 *Komet*[4], whose engine burned hydrogen peroxide with a mixture of methanol, hydrazine, nitrous oxide, and potassium cuprocyanide. This mixture was extremely toxic and exploded on contact with hydrogen peroxide, and the Me-163 landed in flames frequently.

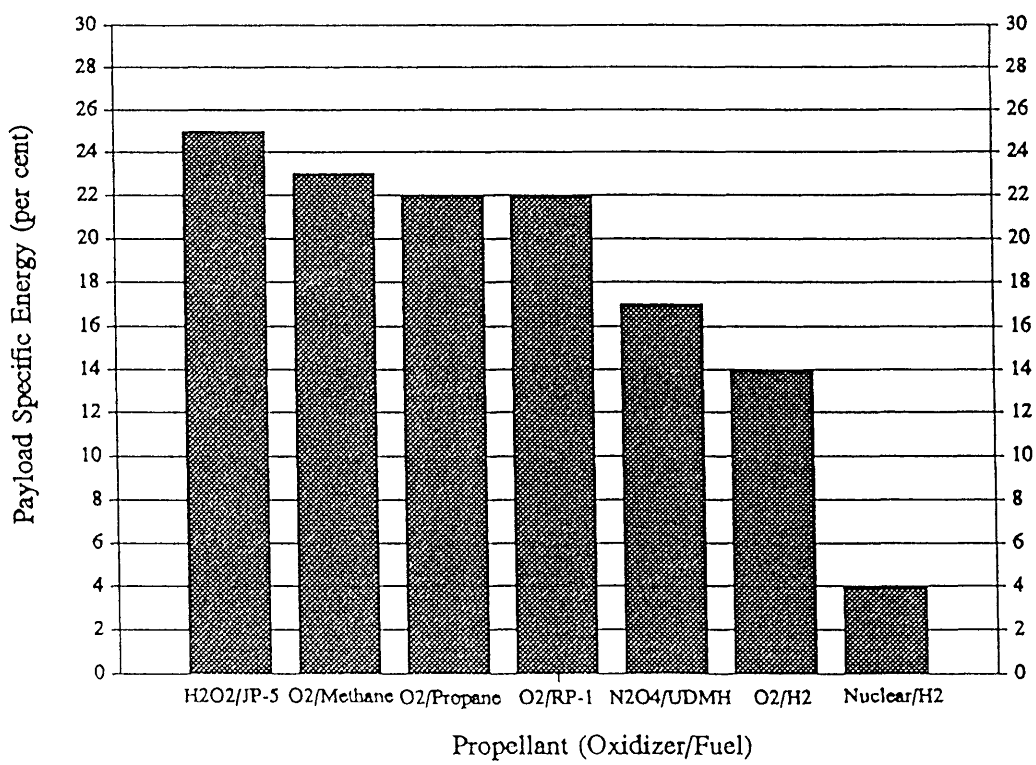

Figure 2: Payload Specific Energy of Candidate Propellants for Single Stage to Orbit

More recently, H_2O_2 has been effective as a propellant in two rocket engine programs. The 6,000 pound thrust AR-2 rocket engine in the NF-104 research aircraft allowed the aircraft to reach altitudes of over 33,000 m (110,000 ft) and return to a powered landing, setting altitude records for aircraft which took off under their own power. The propellants for the NF-104 were ordinary jet fuel for the primary engine, and H_2O_2 and jet fuel for rocket flight above 17,000 m (50,000 ft). H_2O_2 was also used as a monopropellant to maintain attitude control at extremely high altitudes where the aerodynamic controls were ineffective. No rocket engine-related emergencies were noted during eight years of operation, and fuels management was performed using essentially conventional maintenance procedures and normally trained personnel[5].

The other vehicles to use H_2O_2 as a rocket oxidizer on a continued basis were the Black Knight/Black Arrow series of launch vehicles developed by the Royal Aircraft Establishment for the Great Britain Ministry of Technology. The Black Knight and Black Arrow programs lasted from 1958 to 1971. In October 1971, the fourth launch of the Black Arrow placed a 120 kg (250 lb) satellite into a low polar orbit from Woomera, South Australia. The vehicle was about 13 m (43 ft) tall and 2 m (7 ft) in diameter, and its engines delivered a specific impulse of only 217 s (2,130 Nt s/kg) for the first stage and 265 s (2,600 Nt s/kg) for the second stage, both of which burned H_2O_2 with kerosene. Despite these very low performance levels, the vehicle had no trouble achieving orbit and was not of enormous size[6].

The operations procedures of the Black Knight and Black Arrow are interesting. The vehicles were assembled and test-fired on the Isle of Wight, and then shipped to Australia by means of a six week sea voyage. After arriving in Australia, they were trucked up an unpaved road to the launch site, where they were erected and fuelled under essentially field conditions. The structures were unusually sturdy and robust by rocketry standards, and the Gamma 201 and 301 engines were simple and had no advanced controls. The engines were designed to decompose the hydrogen peroxide prior to fuel injection, causing safe and secure thermal ignition without igniters. The H_2O_2 used was only 85 percent pure (the rest being water). The 26 flights in the Black Knight missile and Black Arrow launch vehicle programs over 13 years had no propulsion failures, no launch pad fires, and very low costs by the standards of most rocket programs[7].

Characteristics of Hydrogen Peroxide

Hydrogen peroxide, when pure, is a colorless liquid. The molecule is very stable, but is sensitive to catalysis by impurities. Consequently, the more pure it is, the more stable it is. In concentrations over 99 per cent, it decays in strength by less than 1 per cent per year[8]. Its heat capacity, viscosity, and thermal conductivity make it a better heat transfer medium, pound for pound, than jet fuel, and almost as good as water. It is available commercially for prices between fifty cents to a dollar per kilogram. Table 1 lists a number of properties of H_2O_2[9].

Table 1: Properties of H_2O_2

Molecular weight	34.016
Freezing Point	-0.4 C
Boiling Point	150.2 C
Density (room temp)	1,442.5 kg/m3
Heat Capacity	2.4302 kJ/kg K
Viscosity	0.001249 Nt s/m
Thermal Conductivity	563.8 W/m K
Materials suitable for long term exposure	Aluminum, tin, stainless steel, polyethylene,

Hydrogen peroxide is not toxic in the conventional sense, but like any oxidant, is a powerful irritant to the skin. Flushing with water is usually sufficient to carry away the H_2O_2, and the resulting solution poses no danger to the environment if the final concentration of H_2O_2 is less than 25 ppm[10]. The principal hazard to prevent when handling H_2O_2 is the mixing or contact of hydrogen peroxide with any flammable material in the presence of a catalyst. Provided that the tanks, lines, and other equipment remain clean and never come into contact with potentially catalytic materials, H_2O_2 can be as safe and easy to handle as jet fuel[11].

Detailed thermochemical calculations were performed using tabulated values of enthalpy and entropy and considering the dissociation of exhaust products for the reaction:

$$H_2O_2 + xCH_{1.93} \rightarrow yCO_2 + zH_2O \qquad (8)$$

where $CH_{1.93}$ is the empirical formula of JP-5 and x,y, and z are the mole fractions of the indicated chemical species. The results of these calculations were verified by comparing them with the results of a dedicated propellant performance computer code[12], and several values referenced in the literature[13,14]. Table 2 shows the results of these calculations for the mixture ratio of oxidizer to fuel that yields the maximum value of e_{pl} calculated from equation 7.

Table 2: Performance of JP-5 and H_2O_2

Chamber pressure	21 MPa 3,000 psi
Propellant mixture ratio	
...by mass	7.35
...by volume	4.02
Fuel density	850 kg/m^3
Oxidizer density	1,450 kg/m^3
Propellant density	1,330 kg/m^3
Nozzle expansion ratio	
...in vacuum	180
...at sea level	30
Sea level I_{sp}	295 s
Vacuum I_{sp}	335 s

These values were used to calculate the value of e_{pl} indicated in figure 2. The value of density and specific impulse can be plotted in figure 1, where it falls well above the line for liquid hydrogen and liquid oxygen fuel. These performance figures were calculated assuming a 96 per cent thrust efficiency factor, although the Gamma engine in the Black Knight and Black Arrow projects achieved 98 per cent thrust efficiency[15].

A detailed design for an oxygen/hydrogen-fuelled single stage to orbit vehicle was reaccomplished assuming hydrogen peroxide and JP-5 were the propellants. The component masses were classified as volume dependent (tanks, e.g.), surface area dependent (fuselage, thermal protection system), linear dimension dependent (wiring), empty mass dependent (landing gear), gross mass dependent (engines and engine mount), and invariant (avionics and crew systems). Some of the structural weights were functions of linear dimension and gross weight. A few items (some insulation and purge lines) were removed from the H_2O_2/JP-5 design altogether. A Newtonian iteration was performed to determine the empty mass of the hydrogen peroxide/JP-5 vehicle, which was 29% less than the empty mass of the oxygen/hydrogen vehicle, under the same assumptions. Also, the height of the vehicle was reduced from 128 ft to 75 ft. The gross weight increased by 57 percent, but the cost for a full load of fuel was 48 percent lower, due to the expense of liquid hydrogen.

Operational Advantages of Hydrogen Peroxide

The experience of the NF-104 and Black Knight/Black Arrow programs indicates that the handling of hydrogen peroxide poses no special challenges. Particularly important is the advantage of not having to handle cryogenic materials. Because the vehicle is essentially isothermal prior to flight, no precautions to prevent cryopumping (such as, for example, helium bubbling) are required. The propellants may be stored aboard the vehicle itself, permitting a quick reaction capability. No fuel needs to be expended to chill the engines prior to ignition, and no special gases are needed to purge the fuel or oxidizer lines. Layers of special insulation can be dispensed with, and the large diameter, heavy fuel lines necessary to carry liquid hydrogen are reduced in weight and surface area.

Hydrogen peroxide can be decomposed in the presence of a catalyst to produce steam and oxygen. The reaction is:

$$H_2O_2 \rightarrow H_2O + \frac{1}{2}O_2 + 12.96\,kcal \qquad (9)$$

which would produce a chamber temperature of 1,250 K and, at a chamber pressure ratio of 20, a specific impulse of 146 s (1,430 Nt s/kg)[16]. This reaction can be used as is to provide reaction control for the vehicle, saving the need for separate fuel feed lines to the reaction control motors.

The second application of the reaction in equation 9 is to provide a high temperature, high velocity gas flow in which to burn the fuel. The relative velocity of fuel and oxidizer is the critical term in determining the degree of atomization[17]. Most rocket engines mix their propellants in the liquid state at essentially zero relative velocity. The time scale of the vaporization of the propellants leads to long chambers and an interaction with the acoustic frequency of these chambers that drives a destructive high frequency combustion instability called screaming. Injector design, to assure good mixing and avoid screaming, has thus become an empirical practice of surpassing complexity and subtlety[18]. With hydrogen peroxide and jet fuel, these problems are avoided and the engines become much simpler. Because any amount of jet fuel will ignite in the hot oxygen/steam mixture, throttling becomes an easy matter of adjusting fuel flow and ignition happens automatically without an electrical ignition system.

Hydrogen peroxide also is an excellent coolant. It is the conventional practice to cool rocket nozzles with the fuel rather than the oxidizer. However, as already noted, the heat transfer characteristics of H_2O_2 are superior to those of JP-5. Furthermore, the mixture ratio of these propellants for maximum e_{pl} provides 7.35 kg of H_2O_2 for each kilogram of JP-5. Calculation of the liquid side heat transfer coefficient h_l for both jet fuel and hydrogen peroxide indicates that for a design which permits the jet fuel to rise in temperature by 300 K, the hydrogen peroxide will rise in temperature by only 37 K if all of it is passed through the coolant passages[19]. This is a fortunate result, because hydrogen peroxide that is heated much beyond 100 C tends to decompose into steam and oxygen. Not only will low operating temperatures contribute to longer operating life and greater safety, but cooling with the oxidizer avoids a common problem with hydrocarbon fuel: the deposition of solid carbon in the coolant passages and corresponding burn-through.

Several catalysts are available to decompose hydrogen peroxide. The Black Knight/Black Arrow programs used silver gauze in the Gamma engines. This material is not suitable for use with pure H_2O_2 because the decomposition temperature exceeds the sintering temperature for silver. For pure H_2O_2 permanganate solutions are highly effective, as is platinum. Calcium permanganate deposited on aluminum pellets to provide a reactive surface has been effective as a catalyst in the past. It is also possible to inject the catalyst as a liquid into the fuel stream or oxidizer stream, but this would require another consumable item to be provided aboard the vehicle[20].

Finally, the exhaust products of the combustion of H_2O_2 with JP-5 are predominately 20 percent CO_2 and eighty percent H_2O. Less than 0.25 percent of the propellants are exhausted as carbon monoxide. This propellant combination produces less carbon dioxide per unit of water vapor than conventional combustion of hydrocarbons with liquid oxygen. As such it is more environmentally benign, second only to the combustion of liquid oxygen with liquid hydrogen in this respect. It avoids the release of toxic chemicals into the atmosphere, such as nitrogen-bearing compounds (from burning, for example, hydrazine or nitrogen tetroxide) or halogen compounds (from solid rocket propellants or fluoridated oxidizers).

Alternative Single Stage to Orbit Design

An alternative single stage to orbit design vehicle was designed using hydrogen peroxide and JP-5 as the propellants. A sketch of the vehicle appears in figure 3. The emphasis throughout the design effort was efficient operations, easy maintenance, and simplicity. The mission of the vehicle was to place a 10,000 pound payload of 15 ft diameter and 20 ft length into a polar orbit. A vehicle meeting this specification would be capable of orbiting a 23,500 pound payload by means of a due east launch from White Sands Missile Range, New Mexico.

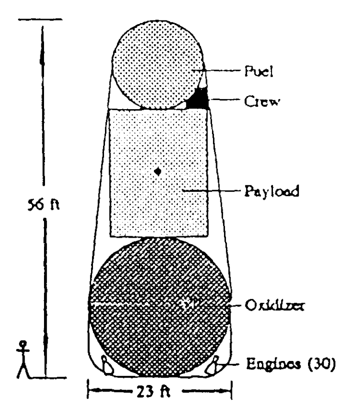

Figure 3: Alternative Single Stage to Orbit Design

The payload sits in its bay at the approximate midpoint of the vehicle. The fuel tank is in the nose and the oxidizer tank is aft of the payload. The payload is located where it is to minimize travel of the center of gravity when the payload is removed. The vehicle is aerodynamically stable in nose first or tail first reentry and can achieve an lift to drag ratio of 0.8, sufficient to give it aerodynamic crossrange of 600 miles[21]. The thermal protection system weighs 1.2 pounds per square foot, on average, and is composed of carbon/silicon carbide, metal multiwall, and thermal blanket materials[22]. The vehicle lands tail first on engine thrust only.

The engines are pressure fed, and operate at a chamber pressure of 14 MPa (2,000 psi). There are thirty engines, arranged in a circle around the base of the vehicle. Each engine has an expansion ratio of 18.5, but the cluster as a whole has an expansion ratio of 366. This yields a specific impulse at launch of 289 s, and in vacuum a value of 335 s. The zero-length plug nozzle configuration causes some loss of efficiency (4.5 percent), but the reduction in weight is favorable[23]. Thrust vectoring is accomplished by individual gimballing of the engines. The tanks are composed of the highest strength to weight material available, Kevlar 49[24]. For all structural components, a weight margin of 15 percent was maintained, along with standard safety factors for pressure vessels and buckling. The vehicle is designed with a takeoff thrust to weight of 1.3, and can lose up to six engines before aborting. Secure intact abort even with multiple engine failure is a key operational requirement for an effective and safe launcher.

The vehicle is 56 ft long and 23 feet in diameter at the base. The empty mass, including payload, is 30,000 pounds. The gross mass is 620,000 pounds. It is designed for a crew of two and an endurance, on orbit, of four days.

Conclusions

A new figure of merit, payload specific energy, suggests that high density propellants can lead to lighter vehicles despite reductions in specific impulse. A particularly attractive choice is hydrogen peroxide and jet fuel, which has a specific impulse of 335 s in vacuum and a density of 1,330 kg/m^3. A liquid hydrogen/liquid oxygen vehicle was reduced in weight by 29 percent when redesigned with H_2O_2 and JP-5. Experience and analysis suggest no special problems and reduced operations costs when using hydrogen peroxide. An alternative vehicle design could provide unprecedented levels of performance, economy, safety, and flexibility.

References

1. Hill, P.G., and Peterson, C.R., *Mechanics and Thermodynamics of Propulsion*, Addison-Wesley, Reading, Ma, 1970

2. Tsiolkovskij, K. I., *The Exploration of the Universe with Reaction Flying Machines*, (title trans. from Russian), Najukizdat', Petrograd, 1903.

3. *Handbook of Chemistry and Physics*, Chemical Rubber Company, Cleveland, Ohio, 1975

4. *The Luftwaffe*, Time-Life Books, New York, 1982

5. *The Aerospace Research Pilots' School*, (curriculum handbook, unpublished), Edwards AFB, Ca 1969

6. *All The World's Aircraft*, Jane's Defense Weekly, London, UK 1971-72

7. Becklake, J. *The British Black Knight Rocket*, JBIS Vol. 43 No. 7 p. 283, July 1990

8. Sutton, G.P., and Ross, D.M., *Rocket Propulsion Elements*, John Wiley & Sons, New York, 1976

9. Kit, B., and Evered, D.S., *Rocket Propellant Handbook*, Macmillan, New York, 1960

10. Liebman, H, *Handbuch der Frishwasser und Abwasser-Biologie*, Gustav Fischer Verlag, Jena pp 719ff, Wasserstoffsuperoxyd, 1960

11. Andrews, D., and Sunley, H., *The Gamma Rocket Engines for Black Knight*, JBIS Vol. 43 No. 7, London, UK, July 1990

12. McBride, B., *A Computer Program for Estimating the Performance of Rocket Propellants*, NASA Lewis Research Center, Cleveland, Ohio 1972

13. Thompson, R.J., "High Temperature Thermodynamics and Theoretical Performance Evaluation of Rocket Propellants," *The Chemistry of Propellants*, Penner, S.S., and Ducarme, J., eds, Pergamon, New York, 1960

14. Williams, R.J., *Theoretical Evaluation of Chemical Propellants*, Prentice-Hall, Englewood, N.J., 1963

15. Andrews, D., *Advantages of Hydrogen Peroxide as a Rocket Oxidant*, JBIS Vol. 43 No. 7, London, UK, July 1990

16. Schumb, W.C., et al, "Hydrogen Peroxide," *Div. of Ind. Coop., Proj. 6552, Report 42*, Parts I-IV, Massachusetts Inst. of Tech., Cambridge, Ma., Sept-Dec 1953

17. Probert, R.P., *Application of Research to Gas-Turbine Combustion Problems*, Proceedings, Joint Conference on Combustion, I Mech. E & ASME, 1985

18. Oates, G.C., *Aerothermodynamics of Gas Turbine and Rocket Propulsion,* AIAA Education Series, Przemieniecki, J.S., ed., AIAA, Washington, D.C. 1988

19. Roshenow, W., and Choi, H., *Heat, Mass, and Momentum Transfer,* Addison-Wesley, New York, 1978

20. Lewis, B., et al, eds., *Combustion Processes: High-Speed Aerodynamic and Jet Propulsion,* vol. II., Princeton University Press, Princeton, N.J., 1956

21. Griffin, M. D., and French, J.R., *Space Vehicle Design,* AIAA Education Series, Przemieniecki, J.S., ed., AIAA, Washington, D.C., 1991

22. Regan, F.J., *Re-entry Vehicle Dynamics,* AIAA Education Series, Przemieniecki, J.S., ed., AIAA, Washington, D.C., 1986

23. Booz, D.E, and Schilling, M.T., *Plug Cluster Nozzle Study Final Report,* NASA contract NAS8-11023 (PWA FR-1013), Marshall Spaceflight Center, 8 Sept 1964

24. Schwartz, M, M., *Composite Materials Handbook.,* McGraw Hill, New York, 1984