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IMPROVED HYBRID ROCKET FUEL

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ABSTRACT

McDonnell Douglas Aerospace, as part of its Independent R&D, has initiated development of a clean burning, high performance hybrid fuel for consideration as an alternative to the solid rocket thrust augmentation currently utilized by American space launch systems including Atlas, Delta, Pegasus, Space Shuttle, and Titan. It could also be used in single stage to orbit or as the only propulsion system in a new launch vehicle. Compared to solid propellants based on aluminum and ammonium perchlorate, this fuel is more environmentally benign in that it totally eliminates hydrogen chloride and aluminum oxide by products, producing only water, hydrogen, nitrogen, carbon oxides, and trace amounts of nitrogen oxides. Compared to other hybrid fuel formulations under development, this fuel is cheaper, denser, and faster burning. The specific impulse of this fuel is comparable to other hybrid fuels and is between that of solids and liquids. The fuel also requires less oxygen than similar hybrid fuels to produce maximum specific impulse, thus reducing oxygen delivery system requirements.

Introduction

The nineties is the decade in which new governmental regulations drove industry to develop and utilize alternative, more environmentally benign products and processes. In the area of rocket propulsion, one effect of the peace dividend has been a reduction in military funding for systems designed to meet military needs, leaving an increased emphasis on commercial launch systems. As a result, technology drivers are being broadened from those of the military, which emphasize low volume and long term storage coupled with immediate readiness, to those established or anticipated to be established by regulatory agencies, which place additional emphasis on safety and being more environmentally benign.

Propulsion Background

The standard rocket propulsion options, the technologies around which all launch systems in use today have been designed, comprise two well defined categories--solids and liquids. Solids tend to be easily stored for considerable periods of time, are smaller, are less expensive to develop, are less expensive in mass production, and are available for use at a moment's notice. However, with minor exceptions, they cannot be turned off once ignited until they have completed propellant burnout. In contrast, liquids allow stop, start, restart, and throttling capability, and are favored for launch vehicle main engines. Commercial systems in use today - - Delta (figure 1), Atlas, and Titan, were

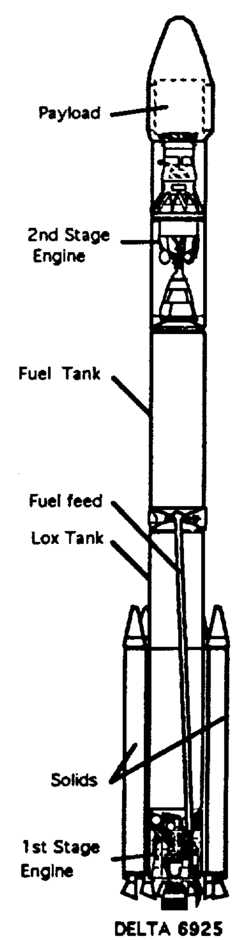

FIGURE 1. DELTA ROCKET

on a hydrocarbon binder system filled with a second hydrocarbon of a slightly different composition. The performance of the MDA hybrid fuel compared to that of the Government/Industry Team's hybrid fuel as well as another possible propulsion alternative is shown in Table 2. The specific impulse developed by the MDA hybrid fuel system compares favorably with others in Table 2. It can be seen that the specific impulse of hybrid fuels is substantially higher than that of typical solids, and is very close to that of existing liquid systems.

Analysis Conditions: Shifting equilibrium, chamber pressure of 1000 psia, solid--70% AP and 18% A1, O/F ratios for RP-1 and hybrids 2.56, 2.4, and 2.0 respectively.

One of the advantages of the MDA hybrid fuel is its higher density compared to other fuels as shown in Table 3. The reason the Space Shuttle needs such a large external tank is that liquid hydrogen has a very low density and occupies a relatively large volume for a given weight. The higher density of the improved hybrid fuel means that the motor case to hold it can be smaller than that required for other hybrid fuels, enabling greater system integration capability with the launch vehicle.

Another advantage of the improved hybrid fuel is its lower oxidizer requirement as shown in table 4. The lower oxygen requirement is advantageous in that a smaller oxygen tank can be used and either a smaller pump or less pressurant will be required to move it, thus reducing weight and cost.

TABLE 1. MOLE PERCENT OF CHEMICAL SPECIES IN ROCKET EXHAUST (AT EQUILIBRIUM)

Exhaust Product	Typical Solid Propellant	MDA Hybrid Propellant
HCl (hydrogen chloride gas)	16.1	none
Al_2O_3 (solid particulate)	9.1	none
CO (carbon monoxide gas)	22.4	27.6
CO_2 (carbon dioxide gas)	1.7	23.2
H_2O (water vapor)	12.4	34.8
H_2 (hydrogen gas)	29.1	6.9
N_2 (nitrogen gas)	8.2	6.2
Total percent accounted for	99.0	98.7

TABLE 2. COMPARATIVE SPECIFIC IMPULSE (I_{SP}) OF DIFFERENT PROPELLANTS IN LBF SEC/LBM

	Solid Propellant	Liquid (RP-1/ O_2)	Government/ Industry Team Hybrid	MDA Hybrid
1 atm	263.1	304	299.2	299.1
Vacuum	288.3	331.2	326.3	326.3

TABLE 3. COMPARATIVE DENSITIES OF DIFFERENT PROPELLANTS

	Liquid Hydrogen	Liquid RP-1	Government/ Industry Team Hybrid	MDA Hybrid
Density in g/ml	0.07	0.81	1.0	1.1

TABLE 4. COMPARATIVE O/F RATIOS FOR DIFFERENT FUELS

	Liquid RP-1	Government/ Industry Team Hybrid	MDA Hybrid
O/F ratio at maximum Isp	2.56	2.4	1.9-2.0

The Hybrid Alternative

Hybrid rocket propulsion is an alternative in which hazardous and environmentally less desirable solid rocket propellants containing ammonium perchlorate can be replaced with a much safer, relatively inert, environmentally benign fuel to be burned with oxygen. A hybrid rocket propulsion system is shown in figure 4. Some of the salient features are 1) the fuel is stored adjacent to the nozzle in what becomes the combustion chamber analogous to solid motors, 2) the total volume of the hybrid motor will be intermediate between a solid and a liquid designed to produce the same total impulse, 3) only the oxidizer needs to be moved to the combustion chamber during operation reducing the number of moving parts compared to an all liquid system, and 4) the complex engine is replaced with a much simpler combustion chamber.

Hybrids--in the form of a solid fuel burned with fluid oxygen--embody many of the advantages of solids. These are a) lower cost via relatively easy design and fabrication to virtually any intermediate size and b) relative simplicity compared to all liquid propulsion systems, since half of the pumping and piping as well as the engine have been eliminated. Hybrids are more advantageous than solids in that they are less costly to handle and process since they are not energetic. From a pollution standpoint, hybrid fuels are advantageous because they can easily be formulated to contain only carbon, hydrogen, oxygen, and nitrogen, (just like liquid fuels) and thus produce primarily water, oxides of carbon, hydrogen, and nitrogen--relatively benign species--during operation. While oxides of nitrogen are possible, the results of analysis obtained via the SPP (Standard Performance Prediction Program) indicate that they are very minor products. Results from this code also show that hybrid systems deliver higher specific impulse than solids.

McDonnell Douglas Aerospace--Huntsville has formulated and tested an advanced family of hybrid rocket fuels. These fuels contain only carbon, hydrogen, oxygen, and nitrogen making them clean burning. The fuels contain no oxidizing species, making them safe to handle, process, and store. The hybrid propulsion system can be started, stopped, restarted, and throttled, and it exhibits more design flexibility than existing hybrid fuels. Tests to date, both in the MDA program and elsewhere, indicate that limited cracks, debonds, or voids in the fuel grain lead to only moderate, slowly developed increases in pressure, making operation safer. These characteristics enable a much wider variety of design options as well as a significantly lowered environmental impact for a rocket propulsion system compared to commercialized solid propulsion technologies.

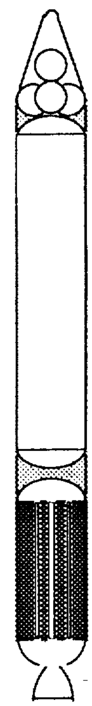

FIGURE 4 HYBRID PROPULSION FOR A SPACE LAUNCH VEHICLE

Characteristics of the Improved Hybrid Fuel

The exhaust products of a typical solid propellant are compared with those of one of the MDA hybrid propulsion options (fuel plus oxygen) in Table 1. The solid propellant formulation is an 18% aluminum, 70% ammonium perchlorate composition, with the percentages being weight percents. The hybrid fuel is burned at an oxidizer to fuel (weight ratio) of 2.0, the ratio at which the specific impulse is maximum. It can be seen that by changing to a hybrid propulsion system which was formulated to be clean, all HC1 and Al_2O_3 are eliminated from the exhaust products. The more hazardous of the two, HC1, is eliminated by replacing the solid oxidizer, ammonium perchlorate, with oxygen. Aluminum was also deliberately removed from this particular hybrid formulation, thus eliminating aluminum oxide from the exhaust.

The hybrid fuel formulation currently being examined by the NASA Marshall Space Flight Center Government/Industry Team is based

Solid propellant is significantly more dense than the components in liquids. Typical solid propellants used in thrust augmentation have densities of 1.84 g/cc. As a result the volume required to hold solid propellant producing a given amount of total impulse is significantly smaller than the volume required for a liquid system designed to produce the same total impulse.

Solid propellants fall into two general types from a safety standpoint. These are class 1.1 and class 1.3, which are explosive hazard classifications. Class 1.1 propellants can react very rapidly in detonation mode as well as more slowly in deflagration mode. Class 1.3 propellants can only deflagrate. However, the difference is only in the rate of reaction, and a slow detonation is very similar to a rapid deflagration. Technically, a detonation proceeds at a supersonic rate. For some compositions under some conditions, a deflagration can accelerate and become a detonation. Because of the relative hazard potential, class 1.3 propellants are preferable to class 1.1 propellants, and class 1.3 propellants are much more common. The fuel in class 1.3 propellants is usually aluminum, while the oxidizer is usually ammonium perchlorate. Thrust augmentation propellants for Delta, Atlas, Titan, and the Space shuttle are all class 1.3.

Solid propellants consist primarily of a fuel and an oxidizer, intimately mixed at the factory long before flight. In most cases the fuel and oxidizer are held together by some sort of rubbery binder material. The common class 1.3 propellants are prepared by mixing the oxidizer and fuel with a liquid prepolymer and a curative. Prior to cure, the mixture is poured or cast into the combustion chamber or motor case. Such motors are known as case bonded since the propellant is bonded directly to the case. (Technically there are intermediate layers of liner and insulation, but they are all bonded together, and the outside layer is bonded directly to the case wall.) The propellant cures in the motor case which becomes the combustion chamber once the motor is ignited and burned.

Two significant chemical by-products produced when class 1.3 propellants burn are hydrogen chloride and aluminum oxide. Hydrogen chloride is a pollutant which contributes primarily to acid rain. The chlorine portion of the molecule can adversely affect the ozone layer. Particulate aluminum oxide can adversely affect the ozone layer if it is deposited in the stratosphere. However, the total amounts of either of these chemicals generated and deposited by rockets is small compared to that generated by all other sources.

Characteristics of Liquids

Liquid propellant systems consist of fuel and oxidizer which are stored and handled separately until they reach the combustion chamber in the rocket engine. Because they are stored and handled separately, liquids are less hazardous than either solid propellants or solid propellant ingredients, especially the solid oxidizers. The most common liquid fuels are hydrocarbons similar to gasoline or jet fuel. The Delta 6925 uses a hydrocarbon called RP-1, which has a density of approximately 0.8 g/cc. The most common liquid oxidizer is oxygen, which is normally handled as a cryogenic fluid to maximize its density and to limit the weight of the tank required to hold it. The density of liquid oxygen is about 1.1 g/cc. The explosive hazard for liquid systems is generally lower than that for solids as neither the fuel nor the oxidizer can explode by itself. However, mixtures of certain ratios can explode and/or detonate. The primary combustion products formed during engine operation are water, hydrogen, carbon dioxide, and carbon monoxide.

Since the fuel and oxidizer are held separately in the rocket, liquid systems utilize pumps to move the liquids into the engine which consist of the inlets, injector, combustion chamber, and nozzle/exit cone. Starting, stopping, and throttling are controlled primarily by varying the pumping rates. There are a large number of moving parts, many moving at very high speeds.

A diagram of one engine (complete with nozzle and exit cone) that is used in the liquid propulsion portion of a space launch system is shown below in Figure 3. Large inlet pipes and powerful high speed turbo pumps are used to supply the engine with fuel and oxidizer during operation.

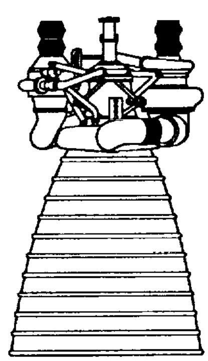

FIGURE 3 LIQUID ENGINE FOR A SPACE LAUNCH VEHICLE

originally designed to use only liquid propulsion. However, over the years, each has subsequently added solid propellant, strap-on, thrust augmentation as a lower cost route to increase payload capability in an incremental fashion.

A good example of a launch system is the 6925 configuration of the McDonnell Douglas Delta Launch System shown in figure 1. This is a two (or three) stage system, with the first stage utilizing a combination of liquids and solids. In the first stage, the weight ratio of oxygen needed for a given amount of fuel is about 2.2. As a result, the oxygen tank is larger than the fuel tank and is positioned closer to the engine. Oxygen is stored as a low temperature, cryogenic liquid, usually referred to as LOX, short for liquid oxygen. At the base of the launch vehicle is the engine in which the fuel and oxygen are combined and burned. The hot gases are ejected through the nozzle throat and expand as they pass through the exit cone shown at the very bottom of the figure 1. Supplementing the liquid main engines, grouped around the base of the first stage are several thrust augmentation units in the form of solid rockets.

The second stage of the Delta 6925 shown in figure 1 consist of a smaller liquid engine with a large exit cone. The much lower external pressure at the high altitudes where this stage operates allows higher engine performance via greater expansion of the hot gases in the large exit cone. The fuel is Aerozine-50, the oxidizer is nitrogen tetroxide, a liquid at ambient temperatures enabling it to be stored without venting which is required for cryogenic liquids. After the second stage is fired, the payload is delivered into a low earth orbit.

In this illustration, the payload is to go into a final higher orbit, and contains a payload assist motor for the last leg of the trip, making the entire package a three stage launch system. Payload assist motors are usually solid rockets, as solid rocket motors are compact and easily stored for long periods of time. This simplifies payload integration, as the payload can be stored and ready well in advance of readying the basic two stage launch system.

Characteristics of Solids

A cross section of the solid rocket motor used for thrust augmentation on the current Delta 7925 Launch System, the Hercules graphite epoxy motor or GEM, is shown in Figure 2. A major difference between the Delta 6925 and the Delta 7925 Launch Systems is that on the 7925, each

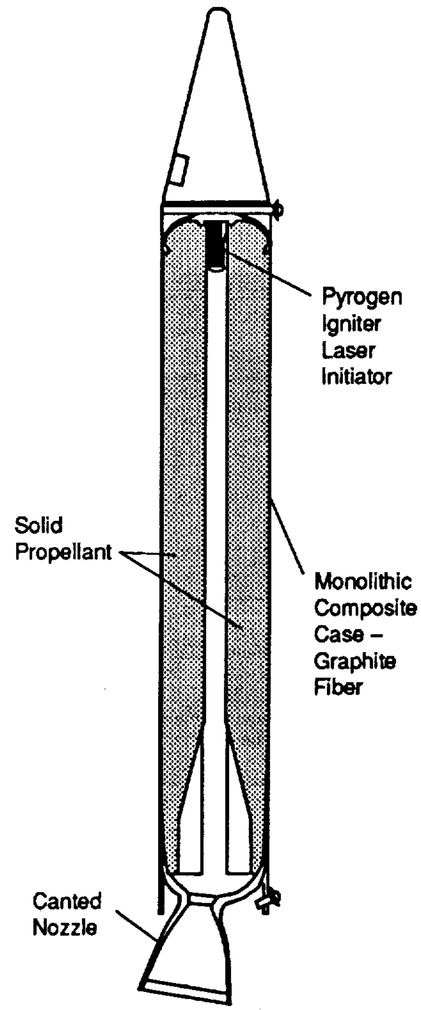

FIGURE 2. THE GRAPHITE EPOXY MOTOR (GEM)

solid propellant motor is larger and utilizes a lightweight graphite epoxy case instead of a metal case.

By examination of figure 2 it can be seen that solid rocket motors are relatively simple, consisting mostly of propellant, case to hold it, an igniter to start it, and a nozzle/exit cone to direct the hot gases. The form of the solid fuel is usually referred to as a propellant grain or a web. In this case, the propellant grain has a hollow core running down the center from the igniter to the nozzle. This type of grain design is commonly referred to as CP, which stands for center perforated. The center perforation is not limited to circular cross sections. The larger open space toward the bottom in this grain indicates some sort of star cross section in part of the grain. The propellant is ignited by an electrical signal and a laser.

McDonnell Douglas has conducted a vigorous IRAD program during 1993 and 1994 to develop these new hybrid fuel formulations. Over 39 motor firings of 2" diameter fuel grains have been conducted with various fuel formulations. The results of the motor firings indicate that the improved fuel exhibits a regression rate approximately twice that of the NASA Marshall Space Flight Center Government/Industry Team formulation. The increase in regression rate will enable a much greater flexibility in grain design. Current regression rate limitations drive the grain design to either a very long, slender, single port grain, or else a complex multiport grain. The increased regression rate will either enable shortening of the single port grain or else a decrease in the number of openings in the multiport design. One net effect will be an increase in the average density since there will be less empty space required in the motor. The resultant decrease in motor size will reduce costs and each launch vehicle integration operations.

During operation the hybrid motor is throttleable and restartable. This provides design flexibility for thrust variation as the vehicle passes through maximum Q compared to solid boosters which provide nearly constant thrust. Test results have also shown that hybrid motors are much less susceptible to overpressurization due to exposure of additional grain surfaces. Cracks in solid propellant grains have a tendency to expose additional propellant surface area which very rapidly produces a positive feedback loop leading to destructive overpressurization. Cracks in hybrid fuel grains have generally been found to lead to only moderate pressure increases since the (fixed) oxygen flow rate limits the total oxidation and formation of additional gas that can occur. In a fairly extreme case which occurred during testing on this IRAD program, grain disintegration and a rapid increase in surface area produced a fairly rapid increase in pressure. However, even under these adverse conditions, detection of the overpressure condition and immediate oxidizer flow shut off resulted in successful corrective action and avoidance of destructive overpressurization.

Potential Uses of Hybrid Rocket Propulsion

Probably the easiest route to implementation of hybrid rocket propulsion technology is through development of thrust augmentation units for use on existing launch systems such as Delta, Atlas, or Titan. The requirements are well defined and the performance of the motor could be extensively validated via a qualification program.

New propulsion systems could also be designed to take advantage of the unique characteristics of the hybrid. One possibility is in the single stage to orbit, reusable launch system. The first iteration in design based the propulsion system entirely on hydrogen/oxygen, a system with a large volume requirement. Subsequent designs have included use of a second liquid fuel with a density much greater than hydrogen, which trade studies have shown results in a gain in overall performance. Since the MDA hybrid fuel exhibits another step up in density, the use of MDA hybrid fuel as part of the SSTO propulsion system should lead to a further increase in system performance. MDA is in the process of evaluating this possibility.

A third possibility for use of hybrid rocket propulsion is a stand alone hybrid for a new expendable launch system. The American rocket Company in conjunction with Martin Marietta plans to fly a small system of this type in 1996.

Ancillary Benefits

In the history of technological development, it has generally been performance first cost second. First determine if it can be done, then determine if it can be done cost effectively. Total cost is made up of indirect as well as direct components. It is easy to obtain cost of raw materials in dollars per pound, and the improved hybrid fuel plus oxygen is significantly cheaper than solids as well as being cheaper than alternative hybrid formulations. However, the total costs of using class 1.3 solid propellants include loss of facilities and buildings, need for additional buildings and land for remote storage and remote processing, and much travel to and from between remote buildings as well as accidents that are inevitable even with stringent attention to safety and quality procedures that have been established for working with energetic materials.

Summary

A family of promising, new, improved hybrid fuels has been developed which offers a number of advantages over solid propellants which they can replace. These advantages include a more environmentally benign system via elimination of hydrogen chloride and aluminum oxide as by-products, lower cost, higher density, higher degree of safety, lower oxygen requirements, and higher regression rates. The advantages are obtained without sacrificing performance as measured by specific impulse. Hybrid propulsion utilizing MDA's new higher performance fuel offers unique characteristics which can potentially increase the performance of the next generation SSTO, or lower costs in existing launch systems as they develop and utilize new larger thrust augmentation units in order to deliver the larger payloads of tomorrow.

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All values involving rocket motor exhaust products or performance were generated using "The Solid Propellant Rocket Motor Performance Prediction Computer Program" (SPP), produced for the United States Air Force by G. R. Nickerson, D. E. Coats, A. L. Dang, S. S. Dunn, D. R. Berker, R. L. Hermsen, and J. T. Lamberty and documented in AFAL-TR-87-078.

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