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ALMOST THERE: RESPONSIVE SPACE

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SpaceDev is developing a hybrid-based small launch vehicle called Streaker™. In addition to providing a low cost (<$5M total) alternative for launching microsats, Streaker is being designed to fulfill multiple responsive space requirements. By their very nature, the building blocks of the Streaker hybrid propulsion system, Nitrous Oxide and HTPB rubber, are inert, safe to handle, and readily storable. Range safety complexity is reduced by reduced toxic material handling requirements and by the Streaker thrust termination capability. Building on extensive hybrid motor testing conducted by AMROC and SpaceDev, the Streaker vehicle is transitioning into a modular launch system family, with configurations capable of either air or ground launch. As part of this development, the infrastructure is being developed to accommodate a mobile ground launch capability, and provision for rapid (hours) launch turnaround. Through a number of on-going programs at SpaceDev, the necessary components of the Streaker, i.e. the Common Core Booster (CCB), hybrid upper stage, and hybrid transfer stage (MoTV) are maturing, targeting a first launch in 2007-08.

Introduction

The Streaker family of hybrid launch vehicles meets the basic requirements for Responsive Space. It is highly configurable, safe to store and handle, and most significantly, affordable. It has sufficient performance and minimal handling complexity to be integrated into a mobile launch program. This paper describes the hybrid motor technology behind the Streaker vehicle, details the configurations available along with predicted performance, and addresses propellant storage and safety considerations. Issues related to rapid launch turnaround and possible integration into a mobile launch system are addressed.

SpaceDev Background

SpaceDev is a publicly owned small business with corporate headquarters and its main design development, and operations facility in Poway, California, a San Diego suburb. SpaceDev was founded as a space products company to bring the microcomputer way of thinking to the aerospace industry. Since 1999, SpaceDev has applied over $16 million of government funding to develop unique and revolutionary microsatellite hardware, systems and satellite networking software and hybrid propulsion products. As a result of the technologies developed, SpaceDev has won over $50 million in government contracts, and over $5 million in commercial space technology development contracts. The current government and commercial business focus is in two areas:

- To develop safe affordable propulsion and launch systems for sub-orbital, orbital and beyond earth orbit manned and unmanned missions.
- To be a leader in the development of affordable small satellites and space vehicles for the commercial and government markets, and for private missions beyond earth orbit and to other planets.

SpaceDev has shown with its recent sophisticated, high performance CHIPSat microsatellite, successfully launched in January 2003, that technology advances in micro circuitry and system miniaturization have enabled small satellites to be built that are capable of carrying sophisticated sensor payloads. Using SpaceDev's standard spacecraft bus and modular

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subsystems, highly capable micro satellites can now be quickly configured for specific missions. The *only* factor suppressing widespread use of small satellites is the lack of responsive and affordable access to space; i.e., current launchers for a $5-million dollar satellite cost $25 million or more, and take months or years to be manifested and launched. While there is currently a mismatch between promising new satellites and existing launchers, we believe that by applying practical new innovations in rocket and launch vehicle technology, SpaceDev can manufacture and supply responsive and affordable small launch vehicles.

SpaceDev Hybrid Rocket Experience

SpaceDev's background and expertise in hybrid propulsion technology was derived from its core of experienced propulsion and launch vehicle engineers from the commercial Atlas program, combined with the knowledge base produced by American Rocket Company (AMROC). In October 1998, SpaceDev obtained the technical rights, proprietary data and patents produced by AMROC, the first company ever to develop and demonstrate the full range of hybrid rocket propulsion systems for SLV boosters. They applied over $25M of private funds to the development of hybrid motor technology, but ran out of money before capitalizing on that investment, and went out of business in 1995. AMROC completed approximately 300 hybrid motor tests from 100 to 250,000 pounds of thrust. One such test is shown in **Fig. 1**.

Fig. 1. Test Firing of AMROC H-1500 Motor

Currently SpaceDev is under contract to develop innovative, hybrid propulsion technology for both commercial and government applications. We have been working with Scaled Composites located in Mojave, CA in applying this safe, low-cost, reusable technology to manned sub-orbital vehicles. We have developed a 20” diameter nitrous hybrid motor that powers Scaled Composites’ manned SpaceShipOne (SS1), (most recently in a record-setting supersonic manned flight on December 17, 2003). This technology serves as the basis for the upper stage for our Streaker small launch vehicle. Our current motor produces over 15,000 lbs of thrust. The first series of test firings on this scale allowed us to fine-tune the fuel grain geometry, main valve and injector designs, and other key variables.

SpaceDev is also constructing a Maneuvering Orbital Transfer Vehicle (MoTV) powered by a hybrid motor under a Phase II Small Business Innovative Research (SBIR) contract with the Air Force Research Laboratory (AFRL). **Fig. 2** is a picture of the hybrid propulsion module for the MoTV, developed with SpaceDev IR&D funding. SpaceDev’s MoTV will be compatible with the Evolved Expendable Launch Vehicle (EELV) secondary payload adapter, and will also be able to be manifested in the Space Shuttle payload bay and meet stringent Space Shuttle safety requirements.

Fig. 2. MoTV during Test Firing of Hybrid Motor

Streaker Concept Overview

Over the past four years SpaceDev has drawn on the hands-on launch vehicle experience of our engineering staff to perform increasingly detailed design concept studies of viable propulsion system candidates for our SLV. **Table 1** compares key benefits of current technology for hybrid, solid and liquid propulsion systems. Due primarily to environmental and safety costs, solid propulsion systems are not likely to achieve the required low launch cost. Hybrid propulsion is a very good candidate and will greatly benefit from SpaceDev's improvements in propellant mass fraction.

Table 1. Comparison of **Current** Propulsion

Factor	Solid	Hybrid	Liquid Bi-Propellant
Command Shutdown & Throttle Capability	No	**Yes**	**Yes**
Non-Toxic Combustion Exhaust	No	**Yes**	Can Be
Ease of Transport, Storage, & Handling	No	**Yes**	**Yes**
Maintenance & Launch Processing Cost	Moderate	**Low**	Moderate to High
Manufacturing Cost	Moderate	**Low**	Moderate to High
Readily Scalable	**Yes**	**Yes**	No
Specific Impulse (I_{sp})	Good	_Good_	**Excellent**
Propellant Mass Fraction	Good	_Fair_	**Excellent**
Safe, Non-Explosive Propellants	No	**Yes**	Can Be Minimized

Our studies show that for a Small Launch Vehicle (SLV) to be competitive in today's market, the design-to-cost constraint **goal is to achieve a launch cost under $5 million per launch.** This will require a SLV system that is: 1) Simple, safe and cost effective to manufacture, integrate and operate and 2) Versatile enough to respond quickly to a variety of launch requirements without modifications. Achieving these characteristics will require the combined application of available technologies not yet combined into conventional launch vehicles. These include:

- Robust, safe, easy-to-manufacture, scalable and modular propulsion systems
- Reduced parts counts for fairings, structures, and separation systems
- Low cost, re-configurable avionics systems
- Standard small payload interfaces

Streaker Vehicle Family

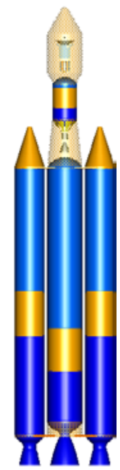
Table 2 shows the components of the Streaker family of launch vehicles, while **Table 3** lists the performance parameters for each stage. Based on hybrid motor technology, but incorporating several enabling technologies that together shift the typical trade space from solid and liquid propulsion systems to hybrid systems. These enabling technologies include:

- Application of low cost ablative engine manufacturing technologies to hybrid motors to reduce cost.
- Incorporation of SpaceDev experience with commercial high thrust hybrid rocket motors such as the motor successfully used on Scaled Composites' SS1.
- Incorporation of SpaceDev's experience with modular high performance avionics used in the CHIPSat small satellite.
- Incorporation of SpaceDev's Maneuvering Orbital Transfer Vehicle (MoTV), currently in development.

Streaker may be air-launched from a standard, unmodified military cargo jet aircraft or ground launched from a mobile ground launcher. The system will be operated with a minimal ground crew and is expected to be easily transportable on its own mobile ground launcher.

The primary new element for the Streaker is a common core booster (CCB). This CCB can be used alone as a core stage for sounding rocket or target applications, or in clusters as strap-on boosters. In this respect, the Streaker follows a modular approach similar to that used on the new Atlas V and Delta IV. The CCB's are described in detail later.

Table 2. Streaker Vehicle Configurations

		
1.0 Suborbital	**Streaker 1.1 (Air-launch)**	**Streaker 3.1 (Orbital)**

Configuration	**Stage 1**	**Stage 2**	**Stage 3**	**Terminal**	**100 nmi, 28.5 deg**	**460 nmi, SSO**
Streaker 1.0	None	CCB	None	None	N/A	Demonstration
Streaker 1.1 M	C-17	CCB	HUS	MoTV	260 lbs	115 lbs
Streaker 1.1	C-17	CCB	HUS	None	N/A	CAV Launch
Streaker 3.0	2 CCB	CCB	None	None	N/A	CAV Launch
Streaker 3.1	2 CCB	CCB	HUS	MoTV	1,260 lb	660 lb
Streaker 5.1	4 CCB	CCB	HUS	MoTV	2,110 lb	1,190 lb

Table 3. Characteristics of Streaker Stages

Streaker Components	**Hybrid CCB Booster**	**Hybrid CCB Core**	**Hybrid Upper Stage**	**MTV Terminal Stage**
Dimensions				
Length (ft)	35.9	37.4	11.0	3.0
Diameter (ft)	5.1	5.1	3.9	2.0
Mass				
Propellant Mass (lb)	39,744	39,744	4,180	346
Inert Mass (lb)	3,456	4,416	570	134
Gross Mass (lb)	43,200	44,160	4,750	480
Propellant Mass Fraction	0.92	0.9	0.88	0.72
Propulsion				
Number of Engines	1	1	1	1
Propellant	N2O / HTPB	N2O / HTPB	N2O / HTPB	N2O / Plexiglas
Isp average (sec)	227	262	269	262
Nozzle Expansion Ratio	10:01	25:01:00	60:01:00	30:01:00
Propellant Feed System	Turbopump	Turbopump	Pressure-fed	Self-Pressurized
Mixture Ratio (O/F)	8	8	6	3.4
Restart Capability	Can be	Can be	Can be	4 starts
Tank Pressurization	Cooled GG Exhaust	Cooled GG Exhaust	HP helium	Self-Pressurized
Thrust (average lbs)	112,700	130,100	13,200	755
burn time (sec)	80	80	85	120
Attitude Control				
Pitch, Yaw	LITVC	LITVC	LITVC	Cold gas N2O
Roll		GG exhaust	Cold gas helium	Cold gas N2O

<u>Ground Launched</u>. The baseline ground launched Streaker has three CCB's, an upper stage derived from our current work with Scaled Composites' SS1, and an optional MoTV final stage for those space superiority payloads that need the mission flexibility and/or orbit transfer capabilities that the MTV provides.

<u>Sub Orbital</u>. The baseline sub orbital Streaker consists of a single CCB, and it can be used for military targets and commercial and government sounding rockets. Its altitude and range varies with payload mass.

<u>Air Launch</u>. The air launch configuration consists of a single CCB topped with a SS1 derived upper stage, and it provides strategic and responsive delivery of payloads on sub-orbital trajectories to any point on the globe. The baseline extraction method is parachutes. This method was validated years ago by tests on a C-5A **(Fig. 3)**.

Fig 3. Air Launch of a Minuteman from C-5A Aircraft

The Common Aero Vehicle (CAV) is an example of a payload that can be sub-orbital delivered. The air-launch platform is all-weather capable, covert, and highly survivable. Because aircraft operations rely on existing infrastructure, no significant new vehicle processing or launch facilities need to be developed. Ocean launch points associated with these down range distances virtually eliminate any hostile enemy risk to Air Force flight crews.

Advantages of our approach are to:

- Minimize vehicle development and recurring cost
- Permit rapid transition from small-scale development to full-scale development.
- Allow for future growth.

Streaker Sizing. SpaceDev will finalize the size of the Streaker.vehicle under our current AFRL contract. Currently, the CCBs are sized at approximately 43,200 lb. With this size CCB, a 2 strap-on configuration can place a 1260 lb payload into a 100 nautical mile 28.5 inclination LEO, or 660 lb into a 460 nautical mile Sun-Synchronous Orbit (SSO). This size CCB is also sufficiently small enough that it can be air launched from a C-17 cargo aircraft. The air-launched version can place 260 lb into a 100 nautical mile LEO.

<u>Hybrid Motor Technology</u>

Hybrid motors typically use a liquid oxidizer such as nitrous oxide or liquid oxygen and a separate solid fuel grain such as rubber, wax, or plastic. The conventional hybrid is a cylinder of fuel with one or more longitudinal passages down the centerline (called ports). Oxidizer is injected at the upstream end, and reacts with the ignited fuel as it travels down the ports, and the combustion products emerge at the downstream end of the fuel grain and then pass through a nozzle. **Fig. 4** presents a conventional hybrid in which the oxidizer is a liquid and the fuel is a solid. A reverse hybrid would have a liquid fuel and a solid oxidizer.

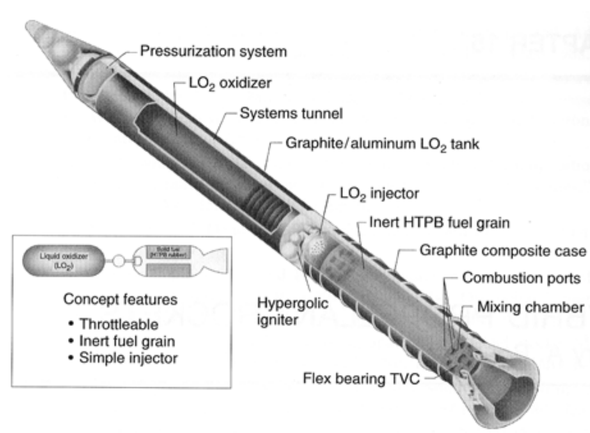


Fig. 4. A Typical Hybrid Rocket[1]

Since the propellants are separated by phase (liquid and solid) and by location, detonation is not possible because there isn't any way for the fuel and oxidizer to mix. Unlike solid rocket motors, the fuel does not contain any oxidizer, and therefore cannot detonate. According to the Department of Defense Explosives Safety Board, hybrid motors can be fabricated, stored, and operated without any possibility of explosion or detonation.[2] However, if their motor cases are inadequately designed or fabricated, a hybrid can burst like any other pressure vessel and, in the presence of an atmosphere, the exposed fuel can burn or smolder.

Other hybrid advantages include the ability to be stopped, restarted, and throttled; easy ground handling (and hence potentially cheaper); and relative insusceptibility to the fuel grain flaws typical of solids. Control and design are simplified since only one liquid needs to be throttled. Reliability is potentially higher and costs are lower since only one liquid must be pumped instead of the two in liquid rocket engines.

Hybrids are in general not expensive to develop. Unlike a solid rocket motor, a hybrid test motor can be started and stopped, permitting detailed evaluations throughout multiple test firings on one motor. This means that development testing can be completed with fewer motors and fewer test firings. Furthermore, testing only one or two ports of a multiple port full-scale motor provides credible test results since the ports are symmetrical. This further contributes to the low cost of developing a hybrid rocket. At a minimum, fuel regression rate verification tests, and some oxidizer injection flow tests are required. SpaceDev has its own highly validated Hybrid motor Analysis Design Code (called HADC), and a fully integrated and tested mobile hybrid motor test facility that includes a PC-based Data Acquisition System (DAS), shown in **Fig. 5**.

Fig. 5. SpaceDev's Mobile Test Stand

Production costs of hybrid motors are much lower than equally sized liquids or solids because of hybrids' greater tolerance to manufacturing defects and lower cost propellants. They can be manufactured in a light industry environment, or at the launch site, with no special safety requirements.

Unlike solid rockets, hybrid motor exhaust doesn't contain hydrochloric acid, perchlorate or other dangerous chemicals. The environmental effect of burning a hybrid's dense hydrocarbon fuel is similar to modern liquid fueled rockets.

These features set hybrids apart from both solid and liquid rocket motors, making hybrids the safest and lowest cost propulsion available.

Propellant Storage Characteristics

The failure of the solid fueled Taurus, Minotaur, Pegasus, Athena as low-cost launch vehicles has led the US Air Force Space Command to conclude that liquid propellants may meet their requirements for low cost and responsive space launch. With a desire to avoid hazardous liquids such as hydrazine, liquid oxygen (LOX) and kerosene are assumed to be the propellants.

However LOX cannot be stored indefinitely at a launch site, because its critical temperature is too low (minus 180^o F). Above critical temperature a substance is a gas, no matter how high the pressure. For example, with the Space Shuttle, 60 highly insulated 4,400 gallon tanker trucks empty their LOX into a huge insulated sphere near the launch pad. Approximately 142,000 gallons of the minus 297.3^o F LOX ends up in the Shuttle external tank, while 100,000 gallons or so boil away during delivery, storage, and filling.

In contrast, nitrous oxide can be stored indefinitely as a room temperature liquid at a launch site in 700 psia (48 bar) storage containers without any boil off. The physical properties of nitrous are almost the same as carbon dioxide since they both have the same electronic structure and molecular weight. Like carbon dioxide, nitrous oxide can be used as a refrigerant in a standard vapor-compression cooling system.

It is difficult to find an oxidizer safer than Nitrous Oxide, N20. It is a colorless, non-toxic, liquefied gas with a slightly sweet taste and odor. When inhaled it produces mild hysteria, sometimes laughter, and therefore is also known as "laughing gas." N20's principal use is as an anesthetic in surgical operations in which it is administered as a mixture of 80% nitrous and 20% oxygen. It is also used as a propellant in food aerosols, particularly whipped cream. Although nitrous oxide is not toxic, it can displace breathable air and can be considered a suffocant like carbon dioxide or nitrogen, but gaseous nitrous oxide can be easily detected by its smell. A cryogenic liquid N_2O spill is easily distinguished because it will rapidly boil away. Small spills of liquid nitrous onto bare skin cause no injuries or damage to clothes. A large spill onto bare skin can cause minor freeze burns.

N_2O is a safe oxidizer in that it is not reactive at room temperature or pressures. It must be heated above 968^o F before it decomposes into 63.7% nitrogen and 36.3% oxygen. Nitrous Oxide handling requires minimal safety equipment and it presents no fire or explosion hazard. It is shipped throughout the country via large tanker trucks and by rail. N_2O is naturally found in the atmosphere at 0.000005% (by volume) for a total of about four hundred million tons. Finally, N_2O is non-corrosive and may be used with common structural materials.

Although there is currently renewed interest in H_2O_2 or High Test hydrogen Peroxide (HTP) as a "green propellant," HTP has serious health and safety problems that complicate its use, especially when using propulsion grade HTP (concentrations greater than 85%). HTP is lethal if breathed in as an aerosol, it will cause severe burns if spilled on skin, and it will spontaneously ignite clothes or other combustible materials. HTP's appearance is indistinguishable from water, making detection of spills difficult. Propulsion grade HTP explodes with the same violence as an equal amount of TNT, and approaches nitroglycerine in terms of sensitivity to shock. HTP can be shipped only in special drums, and there are no current reliable US suppliers of large quantities of propulsion grade HTP. HTP is incompatible with many common structural materials.

For hybrid fuels, candidate fuels include Hydroxyl-Terminated Polybutadiene (HTPB, basically rubber), polyethylene plastic (PE), Plexiglas (PMMA), and paraffin wax. Recent research[3] has demonstrated that paraffin based fuels burn at surface regression rates that are 3 to 4 times that of the other candidate fuels. These high regression rates may eliminate the need for multi-port fuel grains for hybrids. Tests have been limited to using warm gaseous oxygen (GOX), so it is uncertain if these high regression rates occur when cryogenic oxidizers are used.

Note that all of these candidate fuels are more than 25% denser as compared to kerosene; they contain no toxic or hazardous components; and can be shipped by commercial freight as a non-hazardous commodity.

Responsive Technologies

The key characteristics of the Streaker hybrid motor system have been described above. Applying this to the needs of a Responsive Space system, the following advantages become apparent:

Storability - The non-toxic and non-explosive nature of the N_2O and HTPB materials will allow motor subsystems to be stored with minimal logistical support. Nitrous oxide can be stored indefinitely at room temperature in a liquid state. It has very limited boil off loss, so need for replenishment is minimal.

The HTPB fuel materials are extremely robust rubber, similar to car tires. The materials are stable and can handle significant temperature extremes. Therefore, the fuel motor grains can be fabricated and stored in an "enclosed" warehouse environment without special safety provisions typical of solid fuel grains.

The stability of both the fuel and the oxidizer allow the hybrid motors to be stored at remote sites, where replenishment may be difficult. When coupled with the low cost and low safety concerns, it appears to be practical to maintain multiple storage depots adjacent to existing launch pads.

Range Safety – The Streaker hybrid motor technology greatly simplifies the necessary Range Safety documentation. Typically, each launch provider must complete a Preliminary Hazard Analysis and a Missile System Prelaunch Safety Data Package (MSPSP) per the Eastern and Western Range Safety Requirements EWR 127-1 [4]. These documents identify hazardous materials and procedures and provide an overall risk assessment of the system. Identified hazards must have fully documented safety procedures, and may require back-up solutions to reduce overall risk.

Although the Streaker vehicle will not be able to eliminate all of the Range Safety paperwork, it will greatly simplify it. There are currently no flammable or toxic fluids or materials requiring special handling on the vehicle. The DOT has assigned the combined N20/HTPB oxidizer fuel combination with a TNT equivalent of zero, unlike any other standard solid or liquid propulsion alternatives currently under development [2].

It is pointless to develop a rocket motor that has all the inherent safety features characteristic of hybrids, then pair it up with explosive flight termination systems. Fortunately, the Streaker hybrid motor technology allows for the flight termination system (FTS) to be thrust-terminated without explosive ordinance on the vehicle. The possible exception would be a pyro-operated valve/cutter on the main line to reliably sever the oxidizer flow. The Range has already accepted this method for follow-on flights of the Space X Falcon launch system, which is based on LOX/Kerosene propulsion.

Non explosive options will also need to be considered for the flight separation systems. Details of the flight separation will be addressed in the upcoming phase of our Phase II SBIR with AFRL

Rapid Turnaround – Streaker will meet requirements for rapid turnaround in two ways. For the air-launched configuration, the turnaround time is limited only by the number of planes available for the air-launched Streaker configurations. Time needed to land, reload, refuel and re-fly will be hours, not days. There are no limits on the launch vehicle side to the time spent on-station as the fuels do not require replenishment.

Rapid turnaround for ground-based systems will depend greatly on the launch site. However, reduced safety procedures and concerns will streamline the launch timeline significantly. Refueling can be done in parallel with other tasks, rather than waiting until just prior to launch. A limiting factor may be the storage capacity dedicated to N_20.

Regarding the launch site, the ideal scenario for a responsive space system would be the ability to launch from any patch of concrete. Launch operations, currently being developed under Phase II of a SpaceDev AFRL SBIR, will include provisions for mobile launch. Mobile ground operations can be handled by systems such as the Ballistic Missile Range Safety Technology program, currently under development by AFRL's RSLP office.

Summary

The breakthrough SpaceDev Streaker launch vehicle uses hybrid rocket propulsion to its best advantage to reduce the cost and risk associated with launch vehicles to a level acceptable for the Responsive Space mission. There is an air-launched configuration, capable of 260 lb to LEO, and a ground-launched configuration, capable of up to 1,260 lb to LEO. Responsive rapid launch operations are greatly simplified by the non-explosive, non-toxic nature of the hybrid propulsion materials. As the Streaker matures from three test motors to a full launch vehicle, the supporting infrastructure will be designed to retain these advantages as much as possible.

References and Notes

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