Chapter 14:

Flight Testing of Hybrid Powered Vehicles

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Introduction

Hybrid Rocket powered vehicles have had a limited number of flights. Most recently in 2004, Scaled Composites had a successful orbital trajectory that put a private vehicle twice to over 62 miles high, the edge of space to win the X-Prize. This endeavor man rates a hybrid system. Hybrids have also been used in a number of one time launch attempts – SET-1, HYSR, HPDP. Hybrids have also been developed for use and flown in target drones.

This chapter discusses various flight-test programs that have been conducted, hybrid vehicles that are in development, other hybrid vehicles that have been proposed and some strap-on applications have also been examined.

Nomenclature/Acronyms

AFRPL – Air Force Rocket Propulsion Laboratory
eAc - Environmental Aeroscience Corporation
GSFC - Goddard Space Flight Center
HAST - High Altitude Supersonic Target
HPDP – Hybrid Propulsion Demonstration Program
HTPB - hydroxyl-terminated polybutadiene
HYSR - Hybrid Sounding Rocket
IRFNA - Inhibited Red Fuming Nitric Acid
ISP – Specific Impulse
LOX – Liquid Oxygen
N2O - Nitrous Oxide
NGLS - Next Generation Launch Vehicle
NLS - National Launch System
ONERA – French National Aerospace Research Establishment
PLS - Personnel Launch System
SET-1 – Single Engine Test -1 launch vehicle
SLI – Space Launch Initiative
WFF - Wallops Flight Facility

Pacific Rocket Society

Pacific Rocket Society was conducting tests and flight of hybrid rockets in the mid-1940s. The most successful of these units, the propellants consisting of LOX with a rubber fuel, was successfully tested in June 1951 reaching an altitude estimated to be about 30,000 ft.[1]

ONERA and Volvo-Flygmotor

"During the early 1960s, two European organizations became interested in sounding rockets based on storable propellants utilizing nitric acid. These organizations were ONERA in France and Volvo-Flygmotor in Sweden. Both organizations conducted their investigations for about 10 years. ONERA developed a hybrid sounding rocket based on an amine fuel and nitric acid[2] which was 6.3 inch in diameter and 130 inch long, weighing 165 lbs. The motor was throttleable over a 5/1 range to optimize performance. Its first successful flight occurred in 1964 and these flights continued over a three year period eventually reaching altitudes in excess of 100 km (over 10 times the altitude reached by the Pacific Rocket Society about 15 years earlier). "[1]

United Technology Center's Sandpiper/HAST/Firebolt

Also in the early 1960s, United Technology Center and Beech Aircraft, under an Air Force contract, began work on a target drone vehicle based on a storable propellant combination composed of IRFNA as an oxidizer and Plexiglas based fuel. The layout of this motor is shown in Figure 1. [1,3]

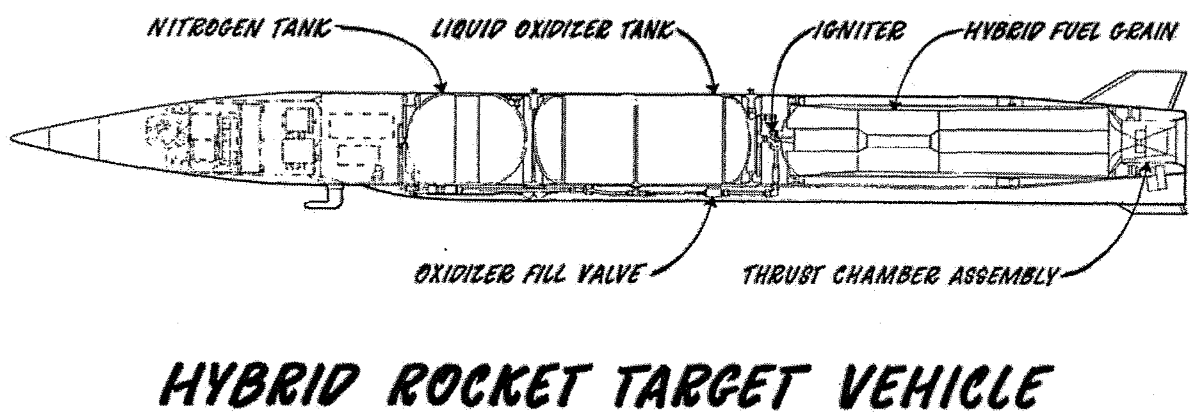


Figure 1 Firebolt Hybrid Rocket Target Vehicle[1]

Originally called the Sandpiper and later the HAST (High Altitude Supersonic Target), the vehicle experienced a series of successful propulsion flights. It was designed to be aircraft launched and to fly horizontally at several altitudes and Mach numbers (up to 5) for ranges in excess of 100 miles. Its thrust duration was 300 seconds and was throttlable on demand over an

8:1 range. The vehicle itself was a modified 180-inch-long version of the Navy AQM-37A liquid bi-propellant rocket powered target missile, with slight modifications.

This work later became the Firebolt target missile system which was under development by Teledyne Ryan. It used the hybrid propulsion system as originally demonstrated in the *Sandpiper* program. The engine, built by the Chemical Systems Division (CSD) of United Technology, was throttleable between 0.53 kN (120 lb) and 5.3 kN (1200 lb). A ram air turbine compressor, with an inlet below the center fuselage, pressurized the IRFNA (Inhibited Red Fuming Nitric Acid) oxidizer before it was delivered to the thrust chamber, and also provided electrical power for the missile. After air launch at about Mach 1.5 from an F-4 aircraft, the hybrid rocket could propel the XAQM-81A to speeds of more than Mach 4 at altitudes of 30000 m (100000 ft). The *Firebolt* could fly a pre-programmed course and/or respond to guidance commands from the ground. The parachute recovery system allowed either a soft landing or a mid-air retrieval. The propulsion system was also tested at AFRPL, with different fuel oxidizer combinations.[3,4] The Firebolt completed it's evaluation period in 1984, however no production contract was ever given.

Starstruck's Dolphin

Starstruck's Dolphin was a prototype vehicle developed to become a sounding rocket and to develop the technology for a planned follow on vehicle called Constellation. The planned Constellation was to be a 4-stage vehicle to get a payload of ~3,200 lb into elliptical geosynchronous transfer orbit. The Dolphin was a 51 ft long, 42-inch diameter recoverable booster, powered by a 35,000 lb_f thrust hybrid rocket. The payload would be 1000 lb_m to 125 mile altitude. The hybrid rocket was developed and tested in Carson City, Nevada. Douglas Ordahl was the bridge person from the hybrid work conducted at United Technologies Chemical System Division (CSD) to the work conducted at Starstruck. Mr. Ordahl was the former head of hybrid propulsion at CSD.

Water launch was selected to reduce the cost required for launch by eliminating the launch pad, increase the orbital insertion options by being mobile and to get around government restrictions on launch from land. However, the decision to perform water launches came with a price.

The launch procedure for the Dolphin was fairly straight forward. The Dolphin was filled with LOX, slid off the boat and floated horizontally in the water. A weight, attached to the aft end of rocket, was dropped into the water and pulled the rocket upright. The nitrogen tanks were pressurized in the water and the vehicle was ready for launch.

On the first launch attempt, on Feb 6, 1984, travel loosened fittings in the nitrogen system used to actuate the valves. Since the vehicle was designed for water launch, access ports were not designed, to reduce the number of water entry points. When an access port was made, by grinding open the intertank, a fire started on some electronic circuits. The positive spin on the event is that it demonstrated the safety of hybrid rockets – no secondary fires from the fuel on board.

The second launch attempt, on March 30, 1984 had a leak to the electronics which allowed salt water to contact with the electronics, which caused the vehicle to shift into abort mode.

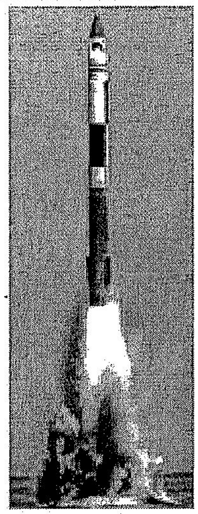


Figure 2 Starstruck Dolphin Launch[5]

The third attempt on August 3, 1984 was semi-successful. Agreements were made to launch the vehicle in protected (less choppy) waters near a military base on an island. Due to the prelaunch restrictions, the planned firing was only to be 15 seconds for a planned apogee of 8000 ft, to keep the vehicle from being able to reach populated land which was ~10 miles from the launch area. The vehicle reached full thrust of 35,000 lb_f thrust at 0.5 seconds into the launch. The vehicle, due to the ocean rocking, came out of the water at a 5 degree angle and was successfully vectored to vertical by the liquid injection thrust vector control (TVC) system(Figure 2). However, a TVC valve stuck closed and the vehicle began to pitch over. Thrust was terminated via telemetry at 14 seconds into the launch, apogee was 2,300 ft at 16 seconds and water impact occurred at 28 seconds. The launch proved hybrids can be safely terminated.

In October of 1984, Starstruck restructured and eventually dissolved.[6,7,8]

AMROC – SET-1

Former members of the Starstruck company formed a new company called American Rocket Co (AMROC) in 1985. AMROC was dedicated to the development of the hybrid rocket for space launch vehicles.

AMROC developed a 75,000 lb motor, which they designated H-500(Figure 3). The first firing was on October, 14, 1987. The motor completed qualification tests on July 11, 1989.

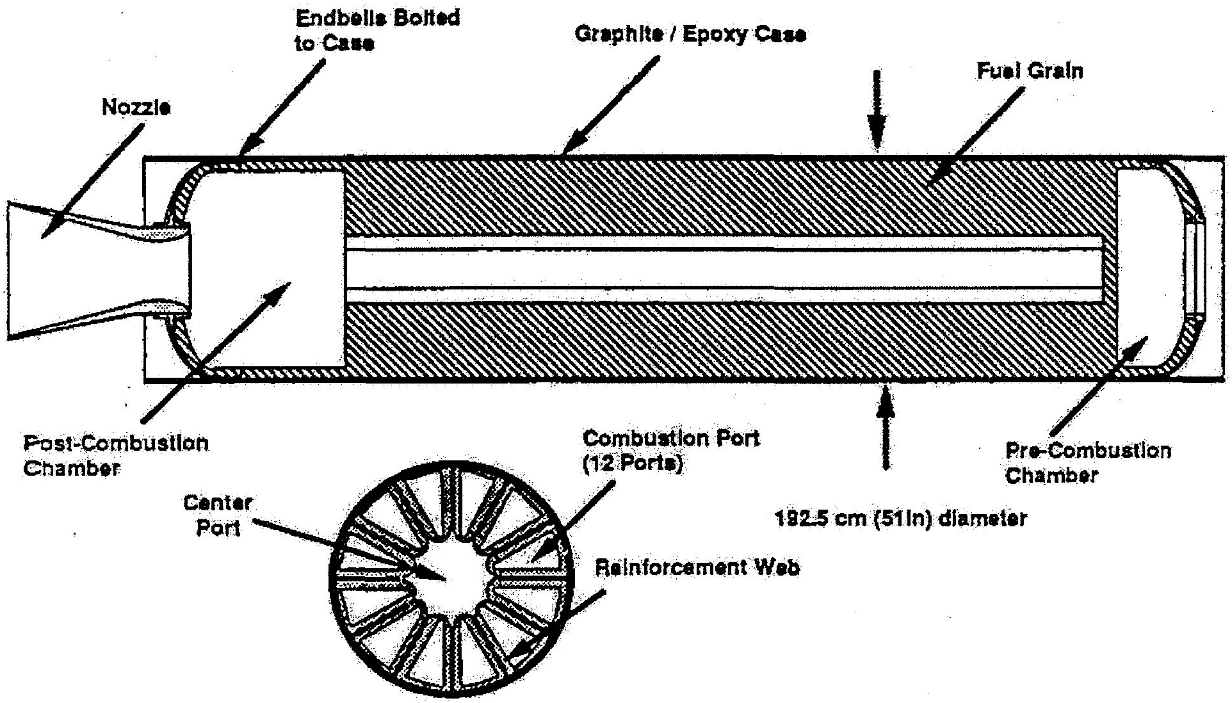


Figure 3 AMROC H-500 Hybrid Motor[10]

The H-500 flight motor was designed to be used on the Single Engine Test-1 launch vehicle (Figure 4). SET-1 was to be a suborbital vehicle which carried two payloads. The launch vehicle (schematically shown in Figure 4) was developed in 9 months for under 5 million dollars. The SET-1 vehicle development included:

-Guidance and Control, Telemetry, Transponder, Power Distribution, Control electronics and Instrumentation,

-Hydrogen Peroxide Liquid Injection Thrust Vector Control System,

-Non-Fragmenting Flight Termination System,

-Catalytic heated helium pressurization system,

-Mono-Propellant Hydrogen Peroxide Roll Control System,

-Launch Pad, Transport and Ground Support Operations and Equipment,

-Integrated Two Payloads: and MIT Space Systems Laboratory Payload and a DoD Payload, and

-Range Documentation, Safety Qualification, and Environmental Approvals for the Vandenberg Air Force Base Launch.[10]

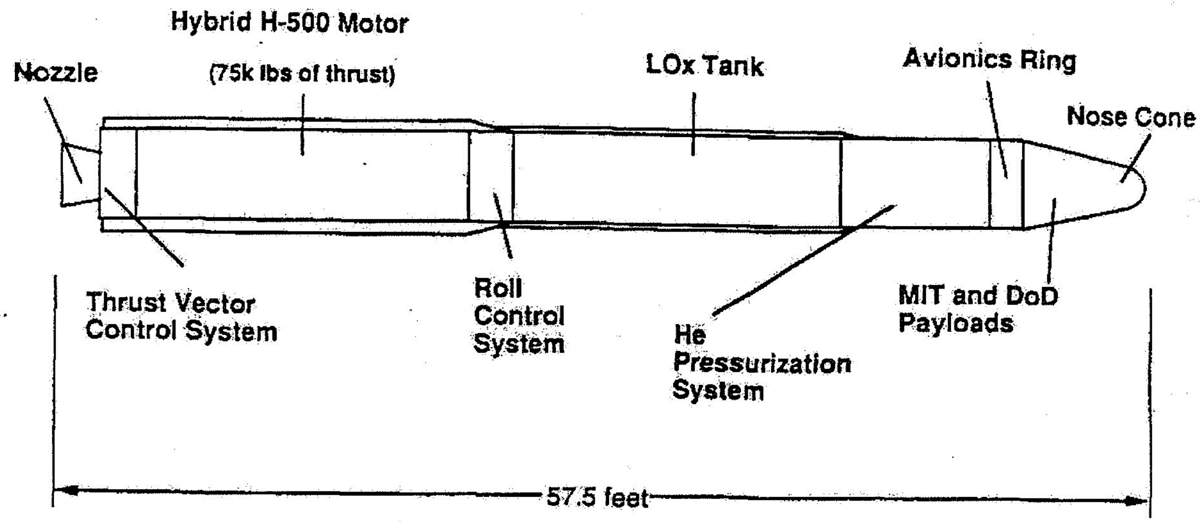


Figure 4 AMROC SET-1 Launch Vehicle[10]

On October 5, 1989 AMROC attempted to launch the SET-1. At the ignition command, the main liquid valve failed to open completely due to moisture which had frozen the valve. Without the full flow of oxygen, the motor developed insufficient thrust for lift-off. Unfortunately, the guidance and control system was issuing automatic commands for a pre-planned pitch maneuver. This resulted in the dumping of a large quantity of hydrogen peroxide liquid injection thrust vector fluid into the nozzle. The hydrogen peroxide began decomposing when it came into contact with the hot flame bucket below the vehicle, which produced oxygen which mixed and ignited with the fuel rich exhaust gasses coming from the motor. The resulting fire in the flame bucket engulfed the vehicle. The aft skirt of the motor case was consumed and the vehicle fell over. The top two thirds of the vehicle suffered only minor damage and the avionics were intact.[10]

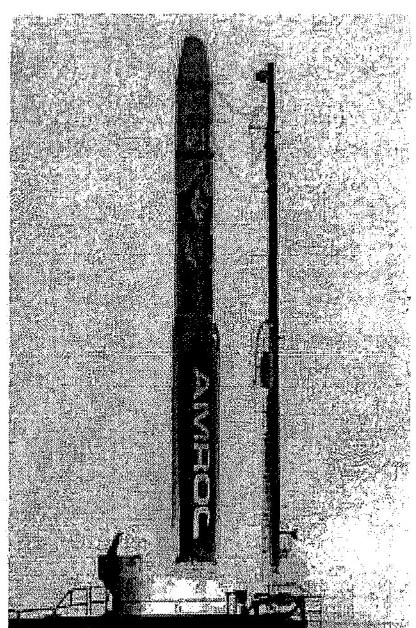


Figure 5 Amroc SET-1 launch attempt[Error! Bookmark not defined.9]

As far as AMROC could tell all the vehicle systems worked as designed except for the LOX valve. There was less than $1,000 damage to the Air Force launch pad. The launch failure was not a fundamental problem with the hybrid rocket motor. In fact, the safety and non-explosive nature of the hybrid motor was proven conclusively.[10]

HPDP Sounding Rocket Flights from Wallops Island

A series of four hybrid sounding rockets were successfully launched as part of the Hybrid Propulsion Demonstration Program (HPDP). These flights demonstrated a safe non-pyrophoric/non-pyrotechnic ignition sequence, inexpensive component manufacturing techniques, simple launch operations, and a quick launch turn around time.

This work was performed under the Hybrid Propulsion Demonstration Program (HPDP), which included NASA/MSFC, Lockheed Martin, Environmental Aeroscience Corporation(eAc), Pratt and Whitney Chemical Systems Division, Allied Signal, Boeing North American Rocketdyne Division, and Thiokol.

The sounding rocket objectives included:

1) Design, fabricate, and launch a series of hybrid sounding rockets, and recover at least one proof of concept demonstration vehicle.
2) Demonstrate a safe, non-pyrotechnic/non-pyrophoric hybrid ignition technique.
3) Perform analysis on the recovered flight vehicle to determine the effects of flight on hybrid propulsion systems and the vehicle.

To fulfill these sounding rocket objectives, a series of four rocket flights using a nitrous oxide (N_20) / hydroxyl-terminated polybutadiene (HTPB) propellant combinations was proposed to demonstrate hybrid propulsion. The first two sounding rocket flights would be low altitude checkout flights in which the hybrid propulsion flight system and launch pad operations would be evaluated. The last two flights would be high altitude flights that utilized a similar vehicle to that which was used in low altitude flights. At least one of the high altitude flights would have to be recovered in order to examine the effects of flight on the hybrid propulsion systems.

The N2O sounding rocket project was divided into five separate development phases:

1) Develop Hybrid Motor to achieve an altitude of 20 nautical miles. This stage of the project included the design, fuel grain modifications, nozzle development, and subscale motor testing using facility supplied N2O. Inexpensive techniques for manufacturing and testing hybrid motor components were also developed. The motor consisted of an annular injector, a 40 long fuel grain and a 1.75 inch diameter glass phenolic nozzle with an expansion ratio of 5.2. Nitrous oxide was chosen as the oxidizer because it is safe, inexpensive, and non-cryogenic. N2O also has a high vapor pressure at ambient temperatures that allows two phase storage and efficient oxidizer delivery thru a self pressurizing process. Therefore, an oxidizer tank pressurization system is not needed, which greatly simplifies the launch vehicle.

2) Design a low cost, flight like oxidizer tank. The tank was constructed of Al 6062 and was welded using a proprietary process developed by eAc. Each flight oxidizer tank was proof

tested to 1.5 times the maximum allowable working pressure of 700 psig. One tank was burst tested to evaluate the material properties and the weld process. Tank design included development of a fill/vent system that would interface with the existing motor design and the Wallops Flight Facility (WFF). The fill and drain system utilized a valveless approach, which is similar to the Hypertek system that is commercially available.

3) Test the integrated system on a vertical test stand. These tests incorporated the flight tank, ignition system, and motor configuration that would be used on the low altitude flights. These tests offered an excellent opportunity to demonstrate the fill/vent process and qualify the function of the rail release mechanism. With this system, the ignition and proper operation of the motor can be verified before release.

4) Checkout of the vehicle at Goddard Space Flight Facility (GSFC) and the two low-altitude launches. This was a complete review of the system, including joint tests, evaluation of mass properties and static balance tests. Data from these tests were fed into the models to predict flight performance. Once the low altitude vehicle was thoroughly reviewed, the vehicle was transported to the launch rail on Wallops island. The first low altitude sounding rocket was launched with a partial oxidizer load and achieved 24,780 ft with no operational anomalies. The second low altitude vehicle, which had been previously checked out, was transported to the same rail and launched within 90 minutes of the first low altitude launch. This was proven to be a successful demonstration of the simple, safe, launch pad operation characteristics of hybrid launch vehicles.

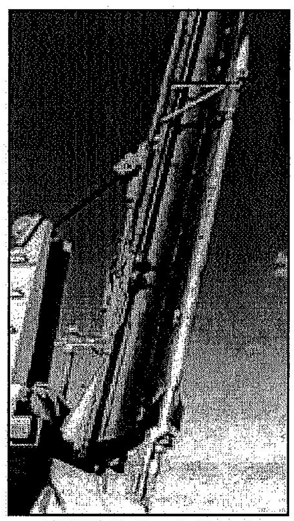


Figure 6 HPDP Sounding Rocket[11]

5) Launch of the high altitude rockets was preceded by some changes to the fuel grain and injector design. The first vehicle achieved an altitude of approximately 120,000 ft and landed within 1.5 sigma of the predicted target point. The second vehicle achieved an altitude of approximately 110,000 ft and was successfully recovered. Post-flight examination of the vehicle indicated no damage to the hardware due to the flight. The fuel grain and nozzle exhibited the same regression and erosion characteristics that were measured on the static tests.[12,13]

The program met all of it's planned objectives:

- A nitrous oxide vehicle was designed, fabricated, and launched in a series of hybrid sounding rocket flights and one proof of concept demonstration vehicle was recovered.

- The flight vehicles' hybrid motors were ignited with a safe, non-pyrotechnic/non-pyrophoric ignition technique.
- The recovered flight vehicle was inspected and the fuel grain and nozzle performed the same in flight as in the ground testing that proceeded the flights.

Another unwritten objective was accomplished – it got hybrids flying again. One issue with hybrid flight concepts/designs presented to various potential customers is – 'have any flight data?' This series moved hybrids in the right direction.[13]

Lockheed Martin HYSR Project

A large-scale hybrid rocket was successfully launched from the NASA Wallops Flight Facility on December 18, 2002 as a technology demonstration for hybrid propulsion and related subsystems. The Hybrid Sounding Rocket (HYSR) program started in 1999. The overall goal of the program was to develop a single stage propulsion system capable of replacing existing two and three stage sounding rockets, with additional objectives to demonstrate the required technology for the launch of a large scale hybrid sounding rocket booster, to demonstrate the positive attributes of hybrid propulsion, to demonstrate two hybrid-based subsystems, and to advance the Technology Readiness Level of hybrid propulsion. The hybrid rocket had a propellant combination of liquid oxygen and hydroxyl-terminated polybutadiene (HTPB) and produced approximately 60,000 lb of vacuum thrust. The three year technology demonstration program was a collaborative effort between NASA and Lockheed Martin and had a total budget under $6M, which was a combination of Lockheed Martin and NASA funding. The program advanced Technology Readiness Level and performance of hybrid propulsion.[14]

Introduction

In order to satisfy the program objectives, a plan was implemented that included static testing of heavyweight test articles, verification of the various components and subsystems, prototype testing of a flight weight test article, and a flight demonstration of the hybrid vehicle. The static testing of the hybrid motor and subsystems would occur at NASA's Stennis Space Center (SSC) and the flight demonstration would occur at NASA's Wallops Flight Facility (WFF).

The HYSR team was composed of personnel from five different centers. Michoud Operations was responsible for the design, analysis, and fabrication of the test articles, flight vehicle, and ground support equipment. NASA-SSC was responsible for test stand fabrication, static testing, and data acquisition during testing. NASA-WFF was responsible for the flight analysis, flight and ground safety at the range, propellants, launch support, and vehicle/payload tracking. NASA-MSFC was responsible for program oversight and to provide funding for the testing at SSC and the flight activities at WFF. NASA AMES Research Center (ARC) would provide a payload and nosecone for the flight.

Prior to the flight demonstration, three tasks were defined to qualify the propulsion system at SSC. Task A contained the static testing of the hybrid motor design within a heavyweight case using facility supplied oxidizer and pressurant. Task B contained oxidizer expulsion system testing from a heavy weight liquid oxygen (LOX) and helium tank that was similar to the flight design. Task C would couple a flight weight oxidizer pressurization system with a hybrid motor to demonstrate a full duration static test that incorporated all of the propulsion subsystems. The vehicle configuration used in Task C was intended to be as close as possible to the flight configuration that could still be tested within the existing facilities at SSC.

Task A – Heavy Weight Motor Testing

Task A testing took place from February to September 2000 at Stennis Space Center's E-3 Complex. Four full-scale motors were tested to gain fuel regression, stability, and performance data to validate the fuel grain design for the HYSR. The fuel that was cast into the motor cases was a mixture of HTPB and high percentage of aluminum to optimize the delivered energy of the system. The motor case center segment had 5 penetrations equally spaced around the circumference of the motor with weldolets used for pass-through Swagelok ™ connectors. These penetrations were used to route the gaseous oxygen to the Lockheed Martin patented staged combustion system (U.S. Patent 5,794,435), which is used for ignition and maintaining combustion stability throughout flight. Figure 7 shows a sketch of the motor case used for Task A testing.

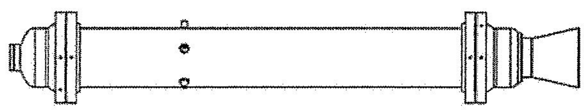


Figure 7 HYSR Heavy weight motor case used for Task A testing[14]

There were two center segment fuel grain configurations tested in Task A due to a redesign that was necessary after Test 2. The initial fuel grain design incorporated 10 quadrilateral ports around a single circular center port. After the first two tests, it was determined that the initial design flux (total mass flow rate divided by the port cross section area) was too aggressive and the port size was increased for future tests to correct this problem. Figure 8 shows a completed heavy weight motor with the facility thrust adapter bolted to the forward dome.

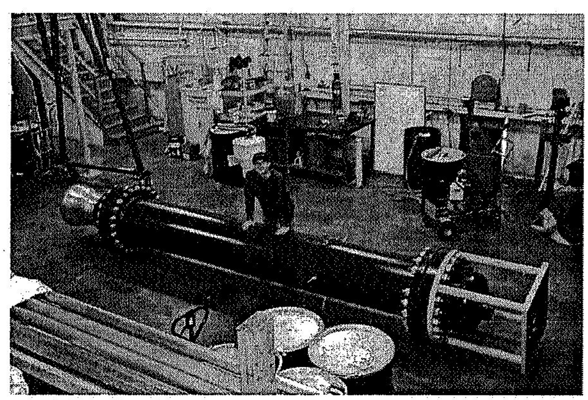


Figure 8 HYSR Completed heavyweight motor assembly[14]

The LOX flow Rate from the 6 foot diameter facility tank for Task A Test 4 is shown in Figure 9. A planned liquid oxygen throttle was demonstrated by initially opening both LOX line ball valves to achieve the maximum flow rate and at 8 seconds into the burn, one of the ball valves was closed to reduce the total LOX flow rate. The LOX flow rate decreases in time to simulate the LOX flow rate expected in the flight vehicle.

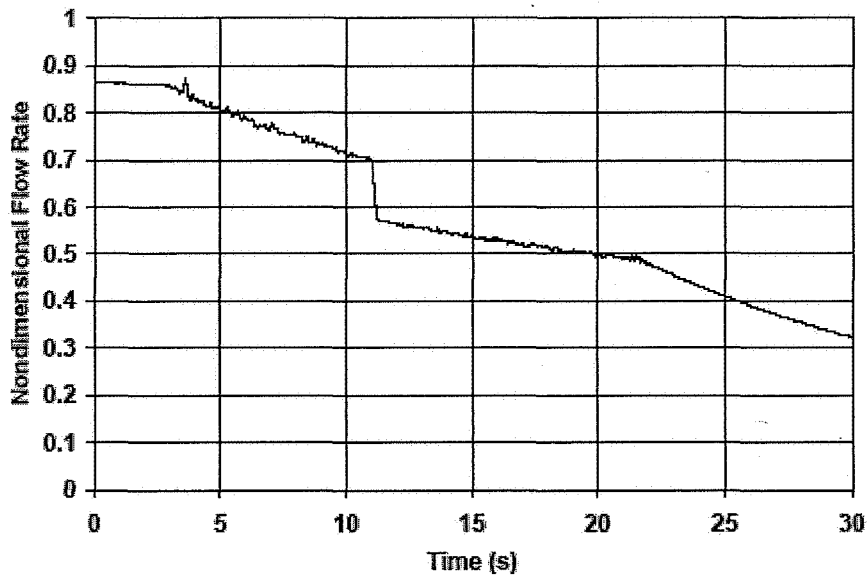


Figure 9 LOX flow rate versus time for Test 4[14]

Figure 10 is a plot of the vacuum thrust from Test 4 of the heavyweight motor test series. The motor was tested for approximately 20 seconds with a planned throttle at 8 seconds into the burn. The vacuum thrust is regressive versus time due to the reduction in propellant flow rate versus time and, to a lesser effect, nozzle erosion. The increase in thrust during the ignition transient was caused by solid fuel being ejected from the motor. The fuel failed due to high loading and weak fuel tensile strength. After the HySR program, Lockheed Martin investigated how fuel failures occur and developed a possible solution to that problem for future hybrids.[15]

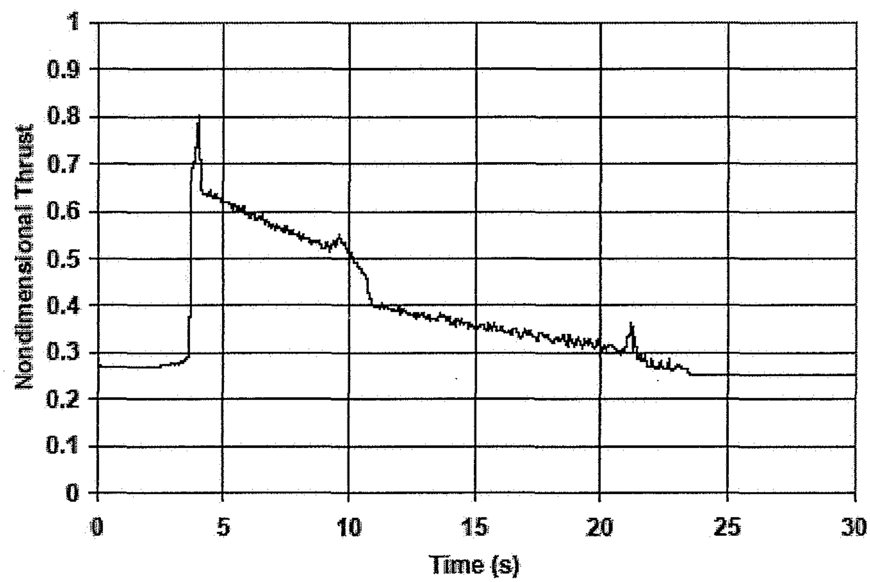


Figure 10 Vacuum thrust versus time for Test 4[14]

Other than the initial ignition transient, the motor performed within a ± 2.5 % stability band around the mean value. The motor also demonstrated a high C* and ISP efficiency.

Task B – Oxidizer Expulsion Testing

The Oxidizer Expulsion Tests were established as a proof of concept and systems refinement exercise for the Lockheed Martin patented heated helium pressurization system (U.S. Patent 5,722,232). The testing took place between September 13, 1999 and January 12, 2000 at Stennis Space Center's E Complex.

Figure 11 is a schematic of the heated helium pressurization system. Helium, initially at cryogenic temperature and moderate pressure, is stored within a spherical tank located at the top of the LOX tank. The system is started by igniting a small diameter hybrid heater and the combustion is sustained with a low flow rate of gaseous oxygen. The exhaust products of the hybrid heater are mixed with helium to create an inert mixture of pressurant. The helium mixture flows through a minimal surface area heat exchanger in the helium tank to attempt to minimize the helium residual. The pressurant enters the LOX tank through a stainless steel diffuser, which disperses the flow into the ullage. The helium-exhaust constituent mixture provides a high energy pressurant that forces the liquid oxygen into the hybrid motor. Storing helium at cryogenic temperatures and then heating the pressurant before it enters the oxidizer tank provides a volumetrically and thermodynamically efficient stored gas system. The mole fraction of the helium in the pressurant gas is greater than 94%, an environment in which no combustion is possible.

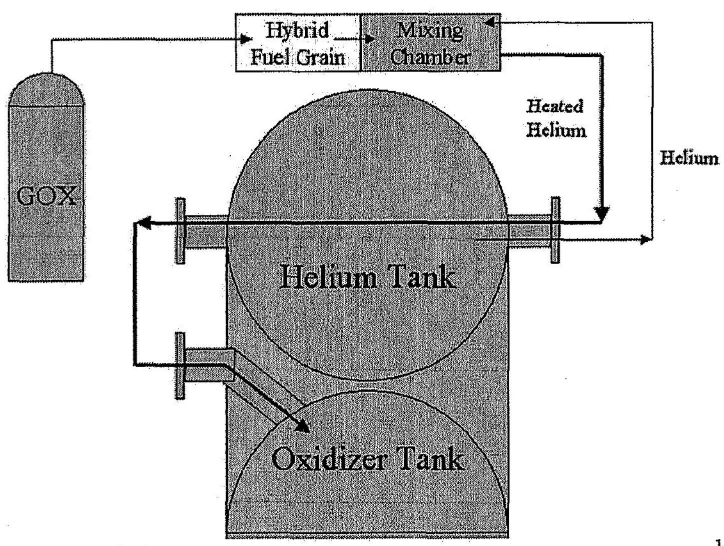


Figure 11 Schematic of the heavy weight heated helium system[14]

Figure 12 is the calculated LOX flow rate from the test tank. The flow rate was calculated using the cavitating venturi flow equation, which is dependent on the upstream temperature, upstream pressure, and venturi throat area. The throttle step that occurs at approximately 10 seconds in Figure 12 is calculated by simply reducing the available area from both venturis to the area of the primary venturi. This step does not actually happen as sharply as shown in the figure. The actual reduction of flow can be best evaluated by the reduction in thrust during the motor test. Also, the calculated flow rate after 33 seconds is not valid. It was evident from the video recordings that the liquid flow ended at this time. The calculated flow after 33 seconds is artificially high because the pressurant has the same temperature and pressure as the LOX (the equation doesn't recognize the difference).

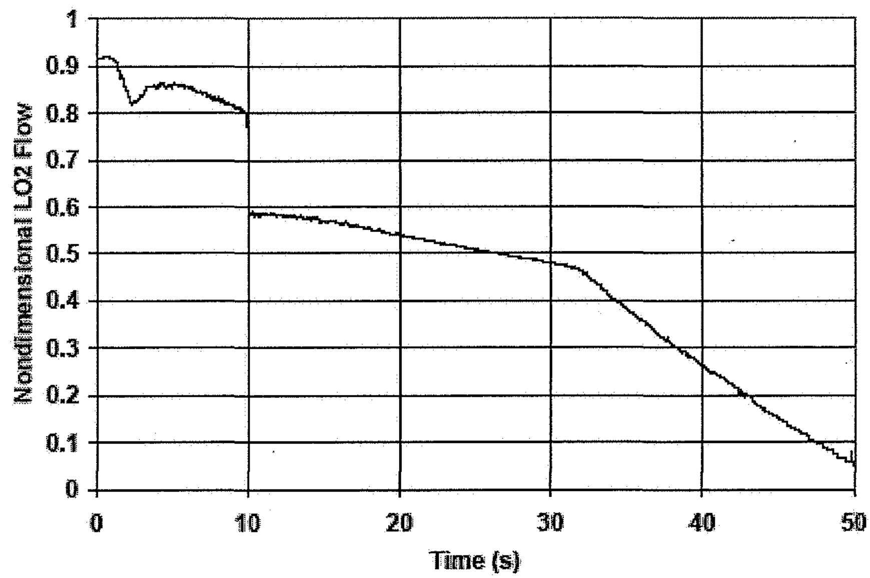


Figure 12 Calculated LOX flow rate for Task B The data after 33 seconds is suspect due to the reasons stated above.[14]

Task C – Integrated Testing

The purpose of the integrated testing was to measure the performance of a prototype flight article to support flight trajectory and dispersion analysis prior to the actual flight. The flight weight hardware and tooling were designed and manufactured at the Michoud Assembly Facility and the testing was conducted at the Stennis Space Center. The helium tank, LOX tank, and motor case are the three primary flight type structures fabricated for this testing. These components were fabricated in the flight configuration with the exception of the payload adapter which was not welded to the helium tank and the forward dome of the motor case had a solid section around the circumference of the dome to interface with the thrust adapter on the test stand. The helium pressurization and GO2 staged combustion sub-systems would incorporate flight weight components, but not in the identical flight configuration.

Unfortunately, the assembled rocket could not be tested vertically within the given budget and schedule constraints. In order to fit within the existing E-3 facility at SSC, the LOX tank was positioned vertically and the hybrid motor would have to be tested in the horizontal position so that sea-level thrust could be measured. This meant that a 90° elbow had to be placed between the vertical LOX tank and the horizontal hybrid motor. This test configuration eliminated the possibility to evaluate the performance of the components enclosed within the intertank compartment, as well as the umbilical feed system.

The integrated test was performed on July 24, 2001. Motor ignition and the subsystems performed as predicted. The testing was manually aborted after the throttle sequence due to a burn through 3 inches aft of the forward insulation. The data collected from the testing was adequate to advance toward the flight phase of the program. Figure 13 shows a photograph of the motor firing during the integrated test.

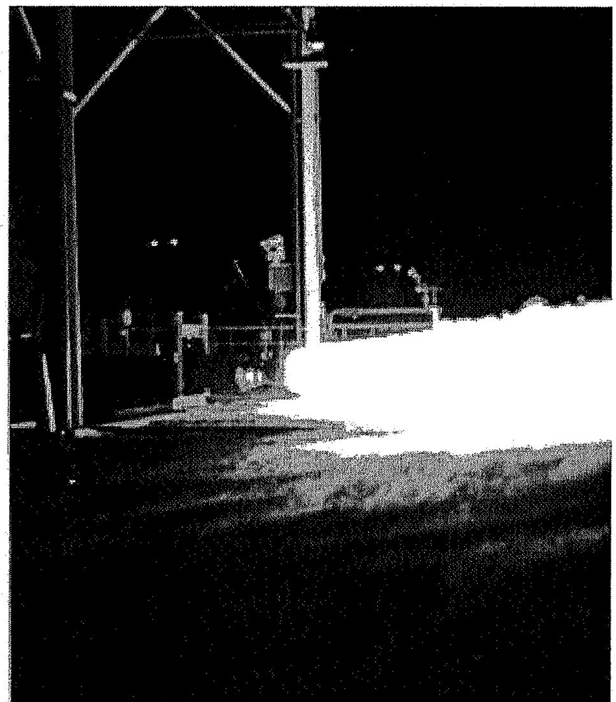


Figure 13 Photograph of Integrated Test Firing[14]

Flight Activities

A rationale to proceed to flight was submitted to Lockheed Martin Management, NASA WFF, and NASA MSFC. The probable cause of the motor burn through was identified and the problem could be corrected by insulating the entire motor case. Multiple oxidizer expulsion and several heavy-weight ground tests were performed and the test data correlated with predictions. With the proper range safety measures in place, proceeding to flight would be less expensive and time consuming than performing an additional ground test. Based on the existing data and proposed corrective actions, it was decided to proceed to flight.

Figure 14 is a photograph of the loading of the assembled vehicle onto the launch rail at Wallops Flight Facility.

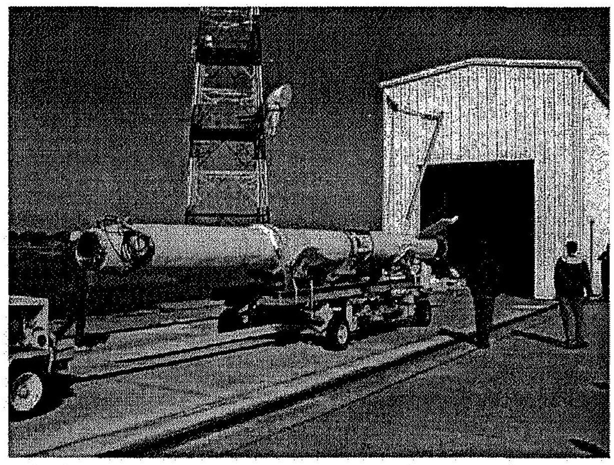


Figure 14 Photograph of the assembled vehicle at the launch site[14]

The payload of the HYSR sounding rocket was provided by NASA Ames and consisted of several suborbital aerodynamic re-entry experiments and ballast. The de-spin section was provided by Lockheed Martin. The objective for this flight was to develop a unique axial ejection technique for multiple re-entry bodies, and to develop the means for testing lifting entry concepts over an ocean range. The ease with which experiments can be performed and integrated, based in part on modular data acquisition/transmission systems, led to it being referred to conceptually as a 'wind-tunnel-in-the-sky.'

A number of dry runs and "wet runs" were performed at the launch rail prior to the launch of the HYSR to establish the loading timeline, verify umbilical separation, and to validate the flightworthiness of the system. These dry and wet runs included erecting the launcher, pressurizing the system, loading with cryogens, cycling valves, deriving fill and conditioning times and cycling the disconnect valves. These demonstration tests revealed a number of issues that had to be resolved prior to flight. Most of the problems involved components that were not in the flight configuration during the ground demonstration. These components had to be retrofitted or repaired after a separate series of lab testing. On August 12, 2002 the final wet run test was performed with no major issues. Figure 15 is a photograph of the HYSR during a "wet run".

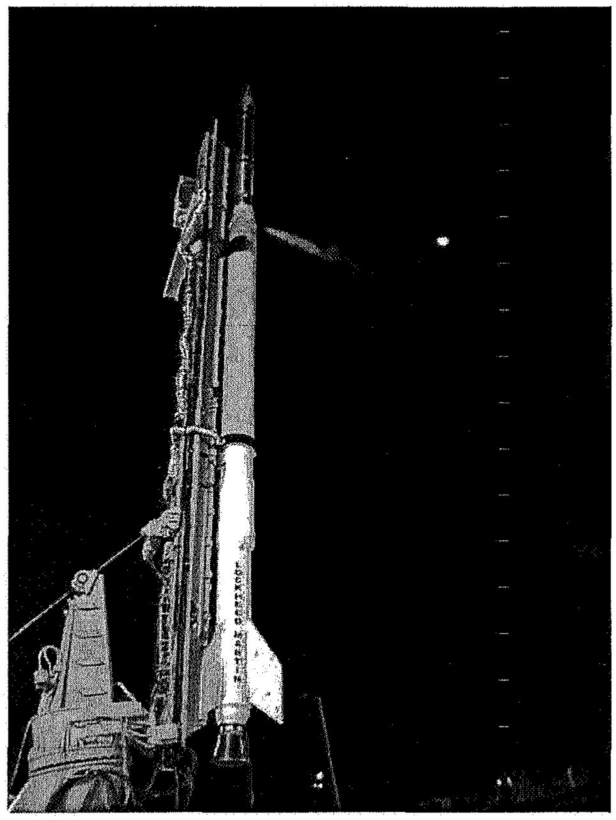


Figure 15 HYSR in the vertical configuration during testing[14]

On the final launch attempt, the LOX and helium tanks were loaded in under 60 minutes. The LOX tank was pre-pressurized to 745 psig at T-10 seconds and the ignition sequence was commanded. After 3 years of development, the HYSR was launched from the Wallops Flight Facility on December 18, 2002 at 6:15 AM E.S.T. Figure 16 is a photograph of the vehicle shortly after ignition.

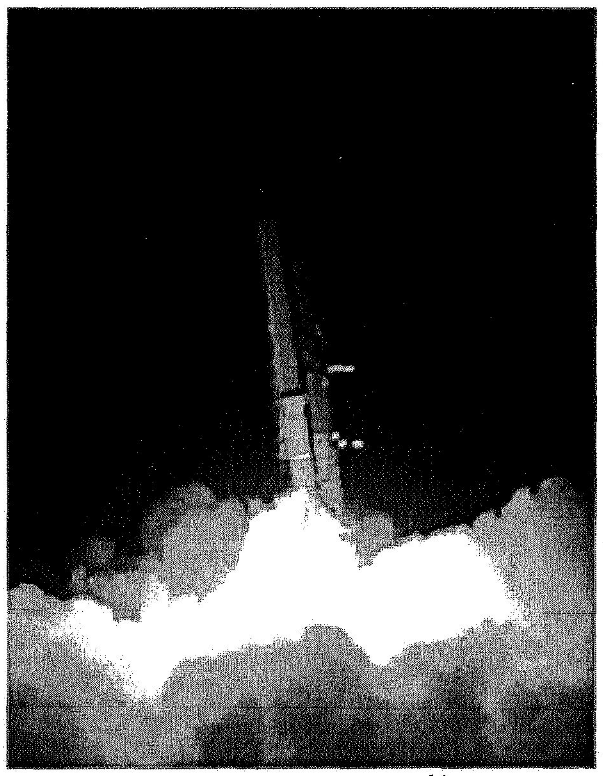


Figure 16 HYSR launch[14]

After an analysis of the flight data, it was concluded that the vehicle achieved an altitude of approximately 42 km, impacted 65 km downrange, and had a time of flight of 213 seconds. The initial acceleration of the vehicle from the rail was approximately 6.1 g's, which was determined from high speed video of the vehicle on the launch rail. The burn time of the motor was approximately 33.4 seconds and the timed despin and payload ejection events occurred as planned. Although the performance was lower than predicted, the factors that reduced the altitude could be explained and performance could be recovered in future missions.

The HYSR flight results proved to be extremely promising. The timer and ejection events appeared to work adequately. Data was acquired for all three experiments. The basic data/transmission system that was identical on the waverider and linear aerobrake worked very well. The flight also provided a unique opportunity to test a unique payload retrieval system for eventual water recovery.[14]

Fredericksburg launches

Fredericksburg High School (FHS) in Texas attained national recognition in 2000 with the successful design, fabrication and flight of a hybrid sounding rocket. The 23-ft, 470-lb rocket, Redbird 9-H, flew to over 35,000 ft, an altitude record for a U.S. high school. This launch from the Army's White Sands Missile Range surpassed a prior year's milestone, which had established FHS as the first US High School to achieve transonic flight when its vehicle accelerated to 833 mph.[16]

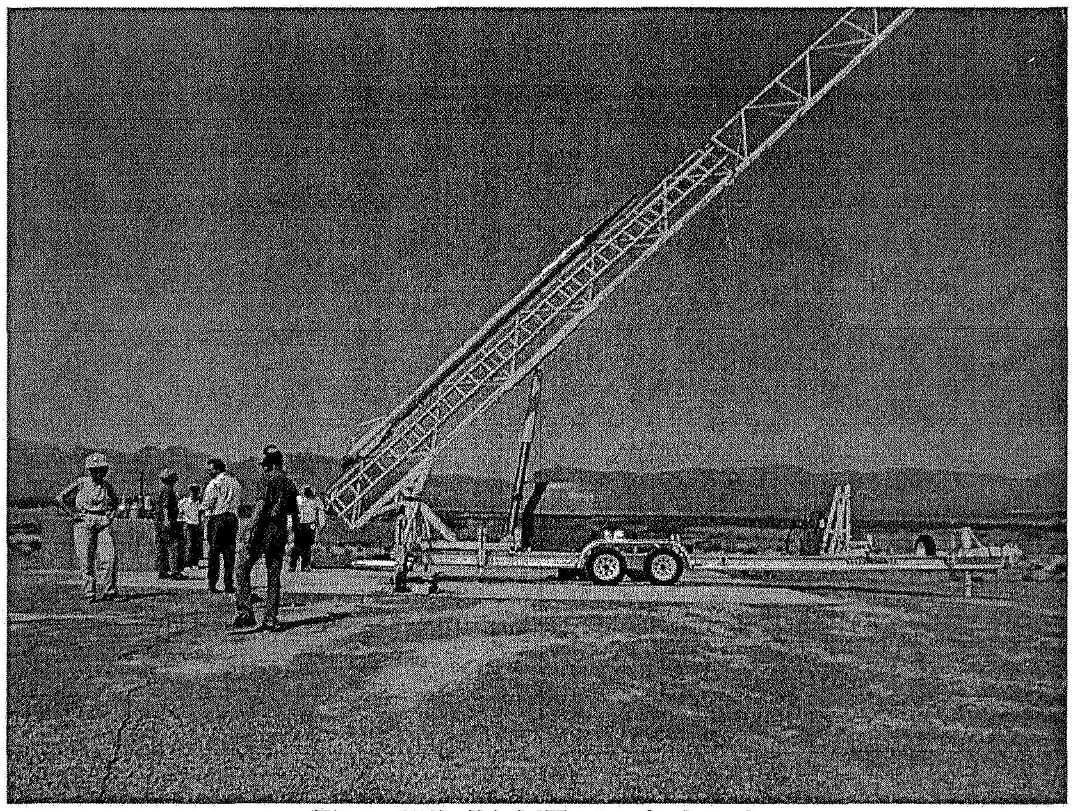


Figure 17 Redbird 9H setup for launch

FHS's program has other motors in the pipeline to be launched.[17]

Figure 18 Redbird 10H Sounding Rocket

Scaled Composites – SpaceShipOne

The Ansari X-Prize was a contest with a 10 million dollar reward for the first commercial company to get 3 people to 62 nm high and repeat within 2 weeks. Scaled Composites built a two stage airplane to win the prize with the second stage plane powered by a nitrous oxide/HTPB hybrid rocket. The first stage air breathing plane, called the White Knight, was designed to carry the second stage to ~ 50,000 ft before it's separation from the second stage, SpaceShipOne. SpaceShipOne's nitrous oxide/HTPB motor was then ignited and fired for ~80 seconds.

With an airplane based system, Scaled Composites could perform an airplane type test program, incrementally testing the flight regions. Scaled Composites performed it's first captive carry of SpaceShipOne under White Knight on May 20, 2003. This test, and a subsequent test on July 29, 2003, demonstrated that the combined vehicles did not demonstrate any unexpected aerodynamic interactions. The first glide test of SpaceShipOne August 7, 2003, with much of the subsonic handling capabilities of the system verified. On the seventh glide test, the nitrous oxide valve and propulsion system was given a full check out by cold flowing nitrous oxide out the motor. The first powered flight on December 17, 2003, consisted of a 15 second burn of the hybrid motor. This short duration burn enabled SpaceShipOne to achieve Mach 1.2 and an apogee of 67,800 feet. This flight was the first privately developed rocket vehicle to reach Mach 1. On April 8, 2004, the hybrid motor was fired for 40 seconds, lofting the vehicle to an apogee of 105,000 feet with a maximum powered velocity of Mach 1.6. Inching closer to a full duration burn, the next flight on May 13, 2004 had a hybrid motor burn of 55 seconds, which reached Mach 2.5 at shutdown and achieved an apogee of 211,400 feet. Another milestone was achieved - the first commercial astronaut flight over 100 kilometers (328,000 ft) occurred on June 21, 2004. This flight had a 76 second burn, powering SpaceShipOne to Mach 2.9 and an apogee of 328,491 ft. The pilot experience approximately 3 ½ minutes of weightlessness near apogee.[18]

The first X-prize flight occurred on September 29, 2004. With a pilot and the equivalent weight of two passengers, the hybrid motor was fired for 77 seconds, propelling SpaceShipOne to Mach 2.92 and a final apogee of 337,700 ft. This flight had a dramatic right hand roll at 190 degrees/sec that was believed to be caused by a lack of symmetry in the hybrid motor thrust with a very low angle of attack. The spin was slowed slightly with the use of aerodynamic controls to 140 degrees/sec, and eventually the reaction control system was exercised to stop the roll.[18]

The second X-prize flight occurred on October 4, 2004 and won the X-prize of 10 million dollars. The hybrid motor was fired for 83 seconds and reached Mach 3.09 at shutdown. The motor reached an apogee of 367,500 feet and exceeded the maximum altitude achieved by the X-15. This flight also experience 3 ½ minutes of weightlessness. The flight test program encompassed 13 months, 17 flights with 6 rocket powered tests.[18] The flight was an historic event and NASA Administrator Sean O'Keefe recognized it in a statement: "Not unlike the first U.S. and Soviet space travelers in 1961, and China's first successful spaceflight last October, these private citizens are pioneers in their own right. They are doing much to open the door to a new marketplace offering the experience of weightlessness and suborbital space flight to the public"[19] Marion Blakey, Administrator of the Federal Aviation Administration (FAA) was on hand for the launch, "This was not only a historic flight, the standards of safety that were set here today are going to go on to ensure that there's going to be lots of tourists out there that'll enjoy it. We'll be partner with you on it."

Blakey awarded pilot Binnie his commercial astronaut wings. The launch team also received a call from President George Bush to express his congratulations.[20]

The hybrid motors worked and performed their missions as designed, however the first X-Prize launch hybrid motor experienced some combustion instabilities - 'This can be heard in the X Prize flight videos as a high-pitched noise. In the videos, visible shuddering which shakes pilot Mike Melville back and forth also indicates nitrous oxide feed problems. This would result from low pressure in the oxide tanks at the end of the engine burn. Nitrous oxide is the oxidizer for the engine's solid propellant.'[21] The second X-Prize hybrid motor also had some minor problems that need to worked on for future systems – 'Partway up some moderate chugging pulsations were seen in the exhaust plume, and he reported feeling vibration at that point. Combustion instability is fairly normal for hybrids and on SpaceShipOne chugging can occur when the liquid nitrous oxide oxidizer runs out, leaving only gas.'[22]

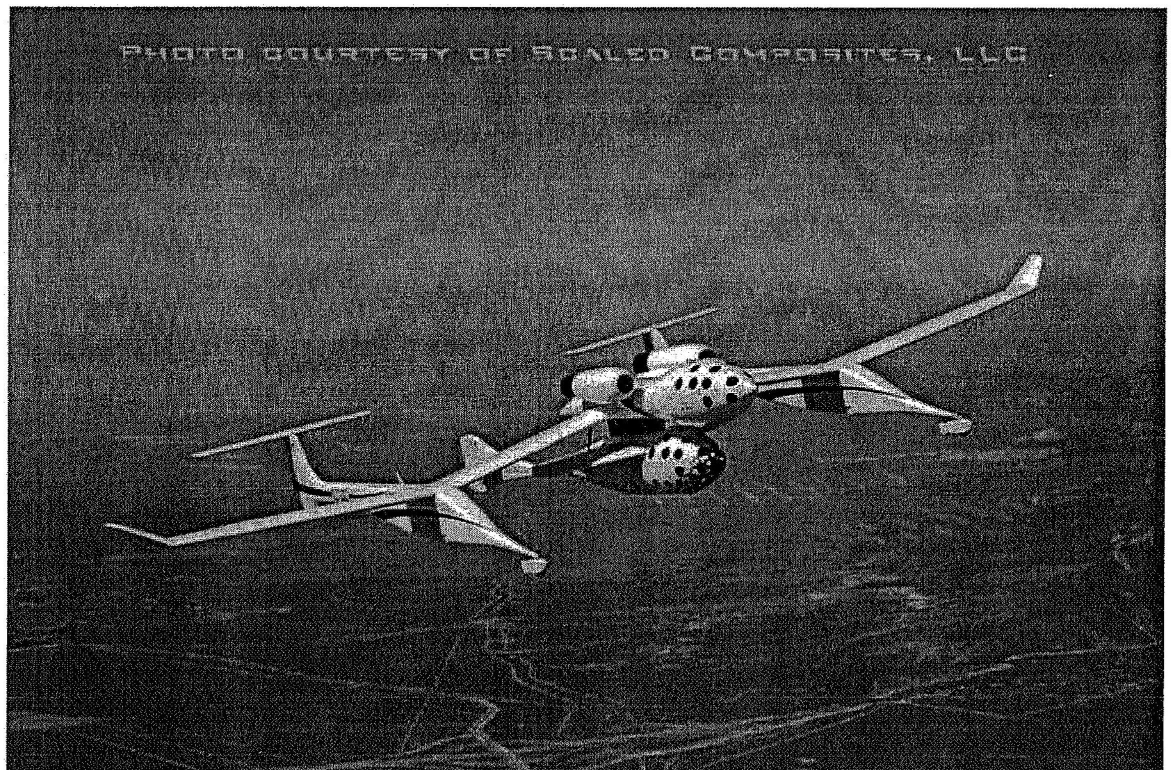


Figure 19 White Knight carrying SpaceShipOne[24]

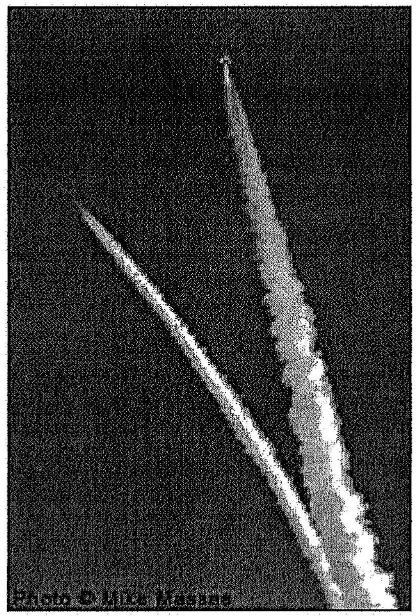


Figure 20 Separation of White Knight from SpaceShipOne[24]

Scaled Composites developed multiple unique and innovative parts of this record breaking hybrid flight system.

- The choice of nitrous oxide allows the system to be self pressurizing. Nitrous oxide has a high vapor pressure, which allows a blow down system. This simplifies the design greatly.
- SpaceShipOne is completely built around the hybrid motor and oxidizer tank. The tank is bonded to the inside of the airframe.
- The nitrous oxide valves were inside the oxidizer tank. This eliminates leak paths and allows the hybrid motor case to bolt directly to the oxidizer tank, simplifying structural loads.
- The hybrid motor included a composite case, with a silica phenolic liner and a carbon fiber epoxy over wrap. Scaled Composites designed the motor case, the nozzle and the oxidizer tank.
- The case had burn thru sensors built into the motor on the interior and exterior of the motor case, so that if any unusual burning occurred, the nitrous oxide valve could be closed and turn the motor off..
- The motor during development was fired for twice the scheduled burn duration to check the motor silica phenolic insulation system. There were no burn thrus.
- The hybrid motor/grain design was competed between two companies with two different motor designs, with a series of test motors fired with the test oxidizer tank. Environmental Aerosciences Corporation (eAc) and SpaceDev both opted to use HTPB, but with different proprietary mixes. eAc choose a single port design and SpaceDev chose a quad port design. SpaceDev was chosen to build cast the hybrid grains for the flight vehicles. eAc's design for some of the oxidizer system plumbing and valves was also incorporated into the flight vehicle.[23,24]

The choice of hybrid rockets for the first privately funded manned space flight launch visualizes the advantages of hybrids – safety, simplicity and performance. It bodes well for the use of hybrids in future applications. – manned and unmanned.

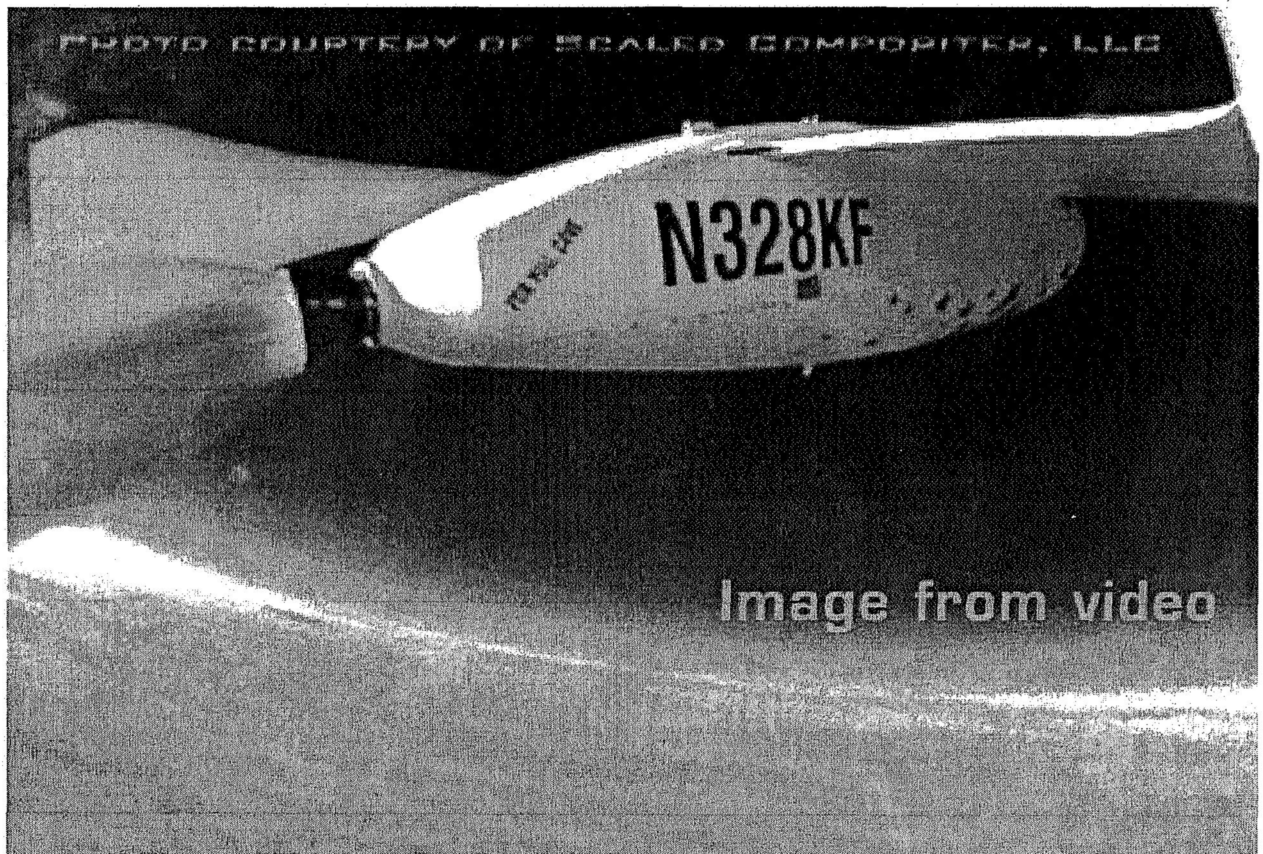


Figure 21 SpaceShipOne's Hybrid Motor Firing[24]

Current Development – Lockheed Martin/DARPA/NASA Falcon

Falcon is a joint DARPA/NASA/Air Force Small Launch Vehicle program to develop and demonstrate an affordable and responsive space lift capability – one that can quickly launch a small satellite into Low Earth Orbit. Under the award agreement, Lockheed Martin conducted a phase IIa preliminary design and development effort to mature its Hybrid launch vehicle design. Lockheed Martin has fired two upper stage hybrids in support of a Phase IIa contract. The goal of the Falcon SLV program is to develop and demonstrate an affordable and responsive space lift capability.[25] The Lockheed Martin vehicle concept is shown in Figure 22.[26] Unfortunately, a follow on contract for this promising concept was not awarded.

Figure 22 Lockheed Martin Falcon SLV[27]

Current Development – Virgin Galactic

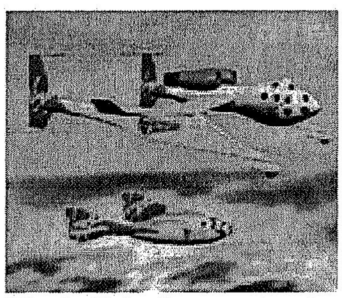


Figure 23 Virgin Valactic space tourism vehicle[28]

Virgin Galactic, a company established by Richard Branson's Virgin Group, is developing space tourism by creating a vehicle based on the Scaled Composite's SpaceShipOne. The vehicle will be reusable and take suborbital rides and will continued to be powered by hybrid rockets.[28] Virgin Galactic is redesigning the hybrid rocket because the new vehicle will be larger and 'because SpaceShipOne's (SS1) engine had low- and high-frequency combustion instability.'[21]

Current Development – SpaceDev Dream Chaser

In 2005, SpaceDev announced a hybrid based launch concept called the Dream Chaser (Figure 24). This six-passenger vehicle could be used separately as a suborbital vehicle or as part of a larger booster system to get it to orbit.[29,30]

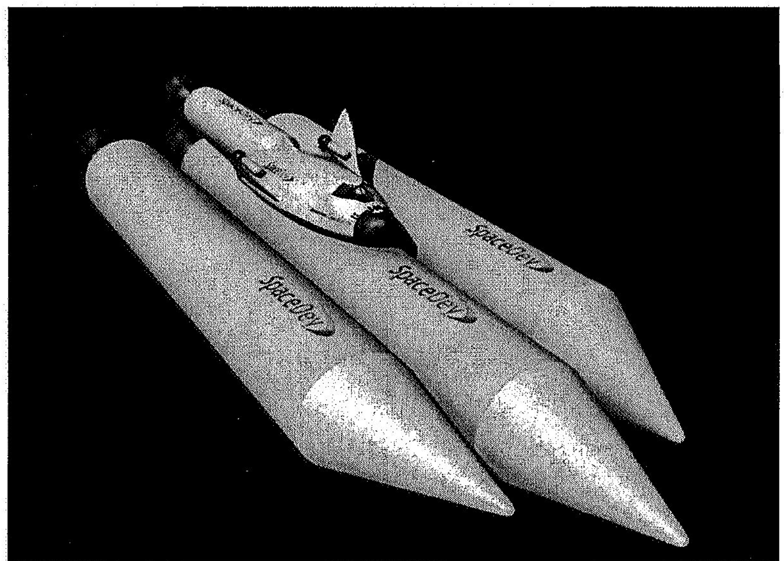


Figure 24 SpaceDev Dream Chaser[29]

United Technologies Corporation Reusable Space Access Launch Vehicle System

US patent 6,726,154 details a 1.5 stage symbiotic hybrid architecture (Figure 25) and an integrated propulsion system - a reusable upperstage with strap on hybrid combustion chambers. All the engines, hybrids and liquids, would fire off the pad and once the hybrids burned out, they would be jettisoned. The oxidizer for the hybrids would be contained in the main vehicle. The potentially high cost components of a hybrid rocket - oxidizer pumps, tanks, pressurization systems, could be reused again as part of the main vehicle. The empty motor cases and nozzles would be jettisoned. This concept was evaluated in the NASA SLI trade studies.

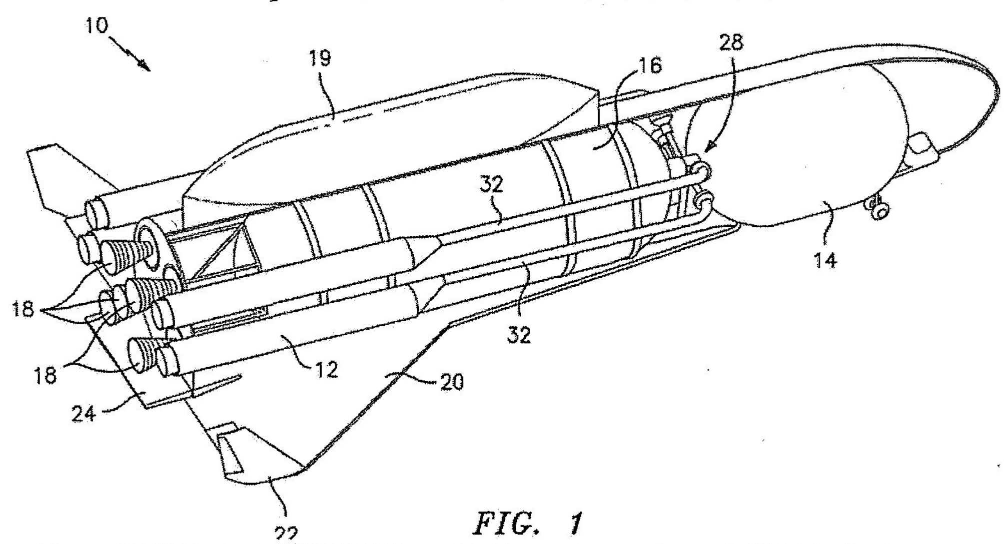
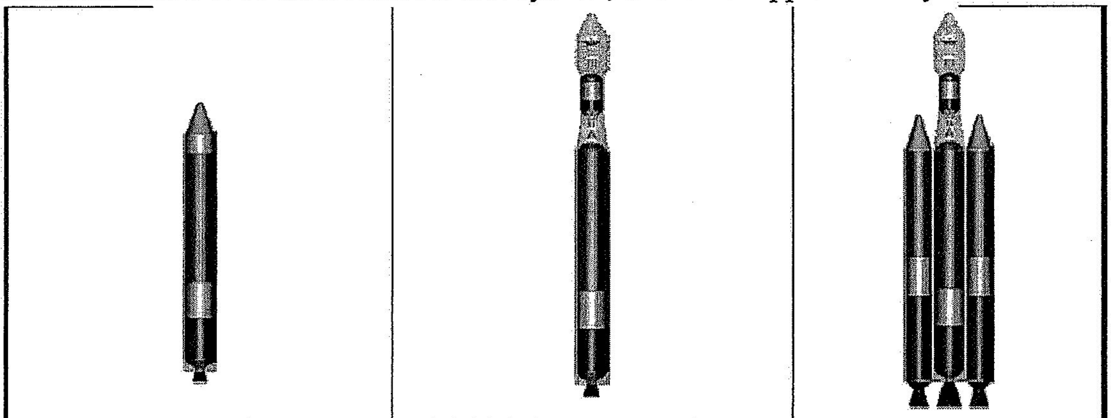


FIG. 1

Figure 25 US Patent 6,726,154 Reusable Space Access Launch Vehicle System

SpaceDev's Streaker Family

SpaceDev has made announcements of it's Streaker family of N20/HTPB based rockets in AIAA papers[31,32], but has since removed mention of the concept from it's website. It may have become a subset of the DreamChasers system, or been dropped entirely.



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

Figure 26 SpaceDev Streaker launch family[32]

Partially developed but never flown AMROC Aquila

After the unsuccessful launch attempt of SET-1, AMROC reevaluated the launch market and saw a niche for a larger vehicle based on a larger 250K thrust hybrid motor. AMROC started marketing the vehicle before testing the hybrid rocket.

In January, 1992, AMROC successfully completed the first development tests of the H-1500 hybrid propulsion system with 225,000 lb_f (1,000 kN) of thrust. Several H-1500 hybrid motors will be clustered together to provide boost propulsion for the Aquila launch Vehicle.

The Aquila Launch vehicle (LV) was to be a ground launched, four-stage, hybrid-propulsion-based launch vehicle capable of delivering up to 3,200 lb_m (1,450 kg) payloads into a 100 nmi (185 km) circular orbit at a 90 degree inclination. The key features of the Aquila LV are shown in Figure 27. These features include the following: a high accuracy inertial guidance, navigation and control system; H-1500 hybrid motor for first and second stage propulsion; an ORBUS 21S solid rocket motor for third stage propulsion; a U-75 hybrid motor for upper stage propulsion and maneuvering; and a 94 in (239 cm) diameter payload fairing for single or multiple payloads."[33]

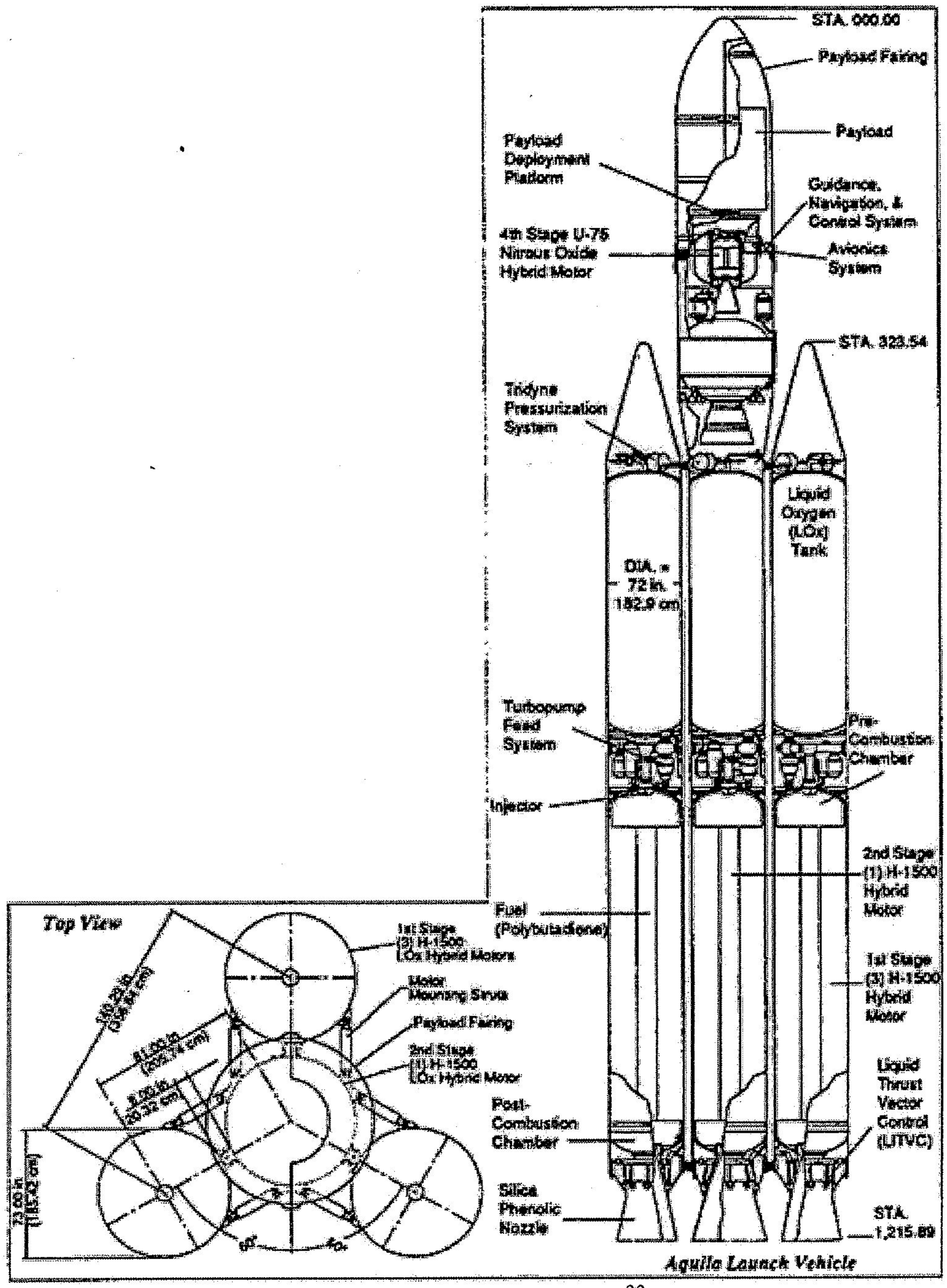


Figure 27 AMROC Aquila Vehicle[33]

The third stage was to be an off the shelf United Technologies Corporation Chemical Systems Division (CSD) ORBUS 21S Solid Rocket Motor. The Aquila fourth stage motor was to be an AMROC pressure-fed U-75 N_20/HTPB hybrid motor.[33] This N_20/HTPB motor was a predecessor to the hybrid used on SpaceShipOne, since Space Dev has purchased AMROC's intellectual property, including designs and test data.

AMROC had decided to pursue the HyFLER as a step to the Aquilia vehicle. The HyFLYER was a suborbital vehicle based on a single H-1500 motor. Amroc tested two H-1500 (250 K thrust) motors and several versions on a nitrous oxide hybrid before the company folded.

Partially developed but never flown AMROC HyFLYER

A joint industry/government team had been formed to develop, build and fly the HyFler sub-orbital launch vehicle powered by a 250,000 pound thrust hybrid rocket motor. The project called the Hybrid Technology Option Project (HyTOP) was co-funded by government and industry and will result in the first demonstration of a large-scale hybrid rocket motor. The team of American Rocket Company, Martin Marietta Manned Space Systems, and United Technologies/Chemical System Division have formed an industrial partnership to conduct the HyTOP effort with ARPA, NASA and the USAF."[34]

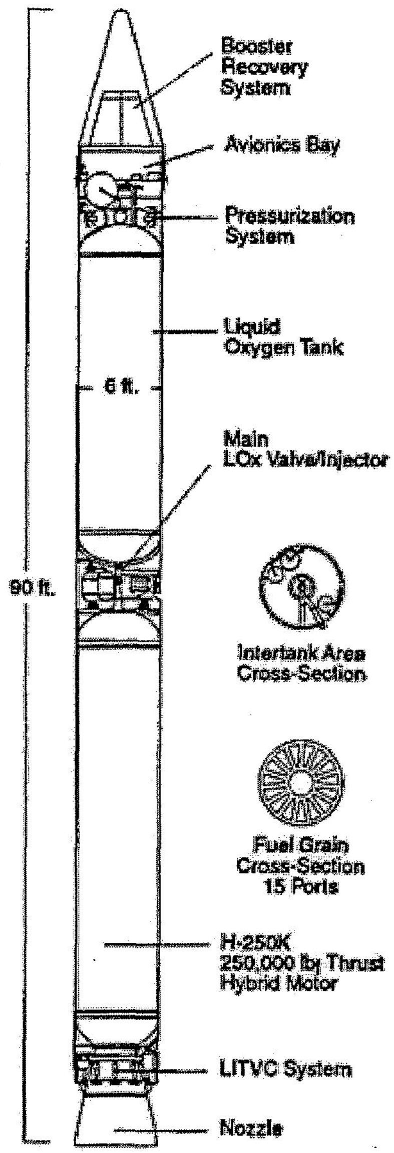


Figure 28 AMROC HyFLYER[34]

HyTOP was meant to be a stepping stone from the Hybrid Technology Research and Development to the Commercialization of Hybrid Rockets. The HyFLYER (shown in Figure 28), was to be the first flight test of the 250K motor. Later, larger vehicles were to be based on this core, with multiple boosters strapped together. AMROC had financial troubles during this development, became insolvent and the vehicle was never finished.

Hybrid Strap-on Concepts

While hybrid vehicles have been proposed and some flown, arguably the best niche for hybrid rockets is in a strap on application for a liquid booster. The relative immaturity of the technology has lead hybrids to be overlooked as strap-ons for liquid systems. Hopefully future hybrid development will open this opportunity for hybrids.

Space Shuttle RSRM Replacements

After Challenger, NASA took a second look at hybrid rockets, with the end application to be the replacement of Space Shuttle Solid Rocket Motors. Several teams of companies examined hybrid rockets for this application, with some results being gas generator hybrids and some being conventional hybrids and the necessary development needed for the system of choice. However, these system studies[35,36,37,38] were not followed with a development program due to the decision to purse an advanced solid rocket motor.

In 2001, NASA was looking at different boost options for the Space Shuttle and included hybrids as one of the alternatives.[39]

AMROC Titan and Delta Strap-on Sizing Studies

In 1992, AMROC investigated upgrading the current launch vehicles of that time by replacing the solid strap-ons with hybrids. "Currently both the Delta and Atlas are using solid rocket motors to augment thrust during the boost phase to increase the payload capability beyond that of the core vehicle. The use of hybrid rocket motors will increase this payload capability another increment. This is primarily due to the fact that the hybrid motor can be throttled deeper than the solid and the hybrid has a higher ISP."[40]

In the case of the Delta launch vehicle, according to AMROC estimates, the use of four 260,000 pound thrust motors (H-1800s) would have allowed for a payload mass increase of 500 pounds to Geostationary Transfer Orbit (GTO). At that time, the Delta used nine GEM solid motors as strap-on boosters.[40]

In the case of the Titan II, an increase of 6,000 pounds to LEO could have been accomplished with the use of two 500,000 lb_f LOX/HTPB strap-on boosters. AMROC calculations showed that this was a benefit of approximately 1,000 pounds over a solution using ten Castor IV strap-ons.[40]

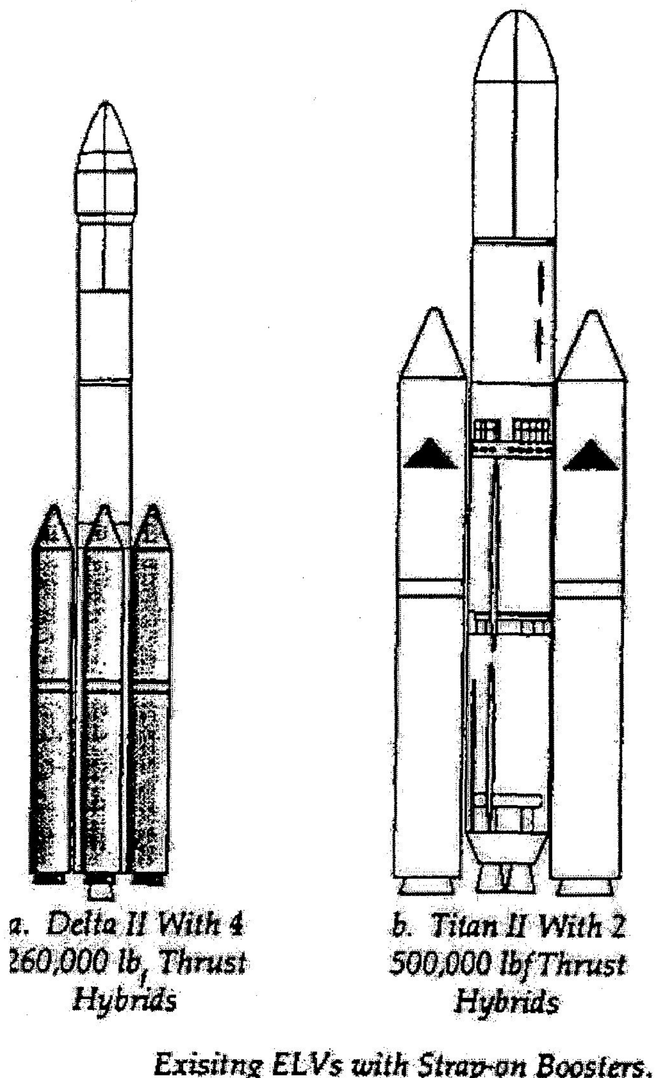


Figure 29 AMROC strap-ons on Delta and Titan[40]

Similar gains could analytically shown by using hybrids as strap-ons for the Atlas II vehicle where the capability to significantly throttle the hybrid can be used to reduce the structural loads on the core vehicle.[40]

Lockheed Martin Optimization Study for Atlas IIAR

An optimization technique was developed by Lockheed Martin and applied to the Atlas IIAR to show the effects of hybrids as strap-ons to the core vehicle.[41] A solid rocket industry standard code, Solid Prediction Program, was converted for analysis of hybrid rocket motors and developed into a subroutine for a Lockheed Martin developed vehicle synthesis tool, FASTPASS.[42] "Analyses indicate a significant potential for payload increases with the addition of hybrid rocket boosters to the Atlas Family of Launch Vehicles. As an example, both pressure-fed and pump-fed hybrid rocket motors were synthesized along with an Atlas IIAR to deliver

10,500 lb of payload to a geosynchronous transfer orbit." The baseline Atlas IIAR is quoted in the analysis as being able to deliver 8,600 lbs to GTO.[41]

AMROC NGLS Strap-on Sizing Studies

In the early 90s, alternatives were being looked at to boosting NASA payloads to orbit other than the Space Shuttle. "Currently, national planners are involved with the analysis and design of the Next Generation Launch Vehicle. During the latest studies of the proposed Spacelifter launch vehicle, a core vehicle was proposed that would utilize strap-on boosters to provide a wide range of payload capability into low Earth orbit. In such a scenario, a hybrid rocket motor provides the premier design option for the strap-on booster due to the hybrid's inherent safety, operational flexibility and low cost. Strap on booster designs are presented that meet the mission goals of 20,000 to 50,000 pounds to low earth orbit."[43]

Using a modified version of AMROCs 250K thrust motor to a longer burn time and higher thrust motor (see Figure 31), a family of launch vehicles were proposed based on a lox hydrogen core vehicle (see Figure 30). Another twist to the concept is to save the LOX/hydrogen core vehicle and just cluster 7 of the larger 280 K thrust hybrid motors fed from a single lox tank (see Figure 32).

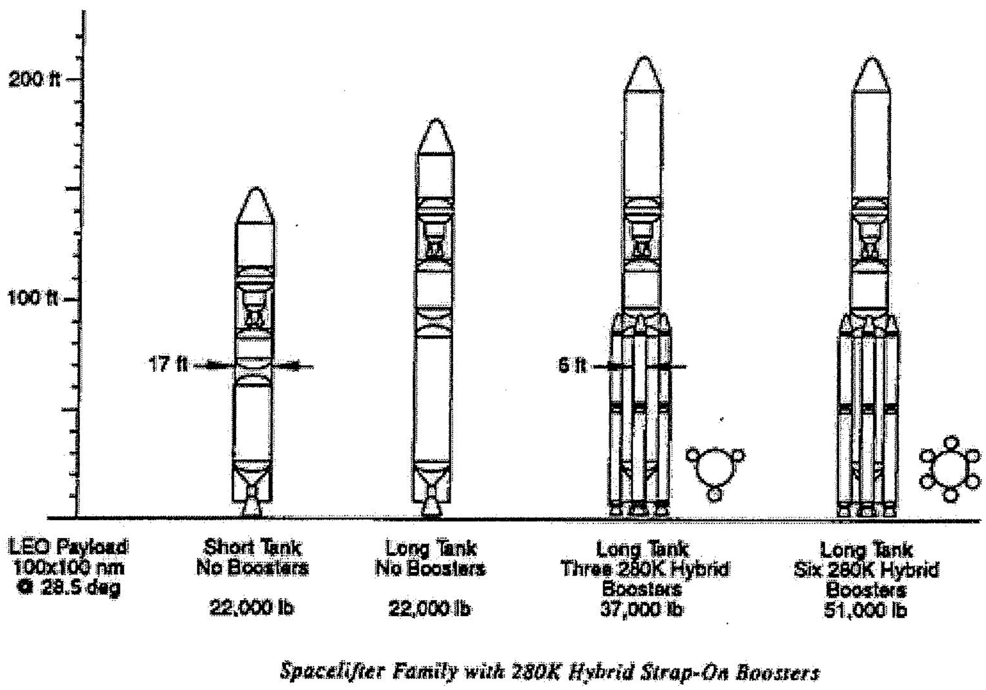


Figure 30 AMROC NGLS type core with hybrid strap-ons[43]

	250K Motor (H-1800)	280K Motor	Difference
Diameter	73 in	73 in	---
Length	30 ft	45 ft	+ 50%
Thrust (sl)	236,000 lb	277,000 lb	+ 17%
Burn Time	72 sec	114 sec	+ 58%
Propellant Wt.	66,500 lb	122,100 lb	+ 84%
# of Ports	15	10	- 33%
Hydraulic Dia.	8.4 in.	10.1 in.	+ 20%

Motor Fuel Grain Configuration Comparison

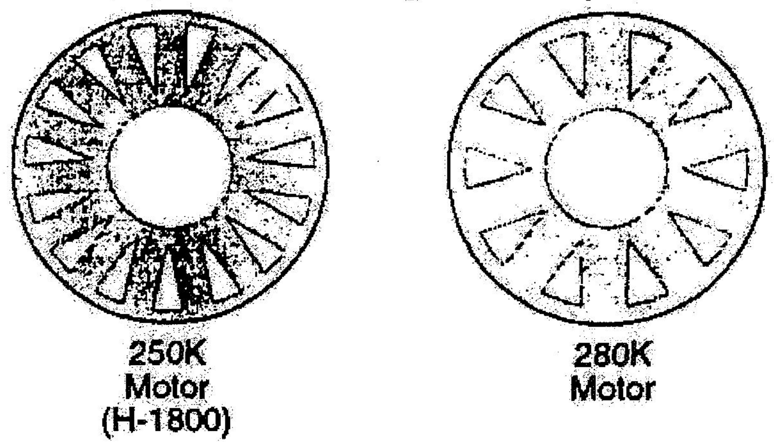


Figure 31 AMROC NGLS Strap-on Hybrid Motor Sizing[43]

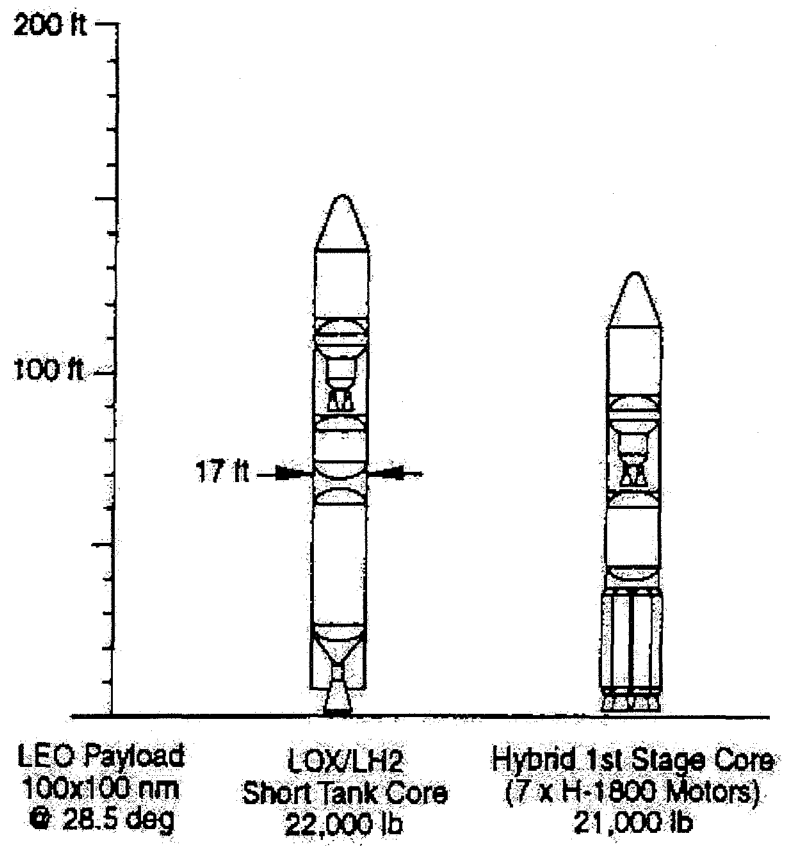


Figure 32 AMROC NGLS type vehicle with hybrid first stage[43]

AMROC NLS and PLV with Hybrid Rockets

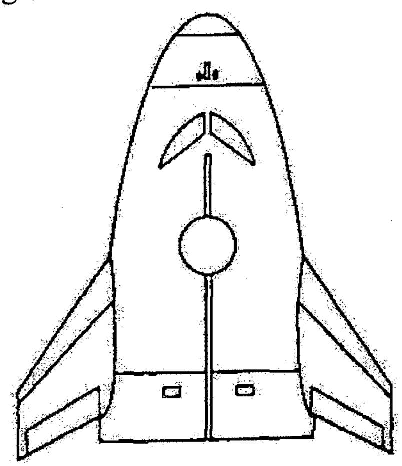
In 1992, two new space transportation concepts were being investigated in the United States. One, the National Launch System (NLS), was being proposed to launch unmanned payloads. Another, the Personnel Launch System (PLS), was a small spacecraft designed exclusively for personnel transport. Consideration was given to launching the PLS using an element of the NLS booster. The demanding requirements for crew safety and safe return after abort indicated that the PLS may be better served by a launcher optimized for crew safety, leaving the NLS to be optimized for it's unmanned cargo carrying load. The unique safety characteristics of hybrid propulsion could have been invaluable in this manned launch role.[44]

All forms of rocket propulsion can claim the potential for high reliability. Increased reliability generally is accompanied by increased complexity and inspection requirements. Mission reliability is not, however, the most critical factor where manned systems are concerned. The paramount issue in manned system planning is not how likely a failure is, but what are the consequences of a failure if it occurs.[44]

With conventional solid and liquid propulsion systems, to ensure crew safety and minimize the likelihood that catastrophe will occur, considerable effort is spent on maximizing system reliability. In addition, complex and often troublesome health monitor systems are required to give advanced warning of impending failure. This is necessary to allow time for emergency escape systems to carry personnel to a safe distance, away from potentially life threatening explosive blast waves.[44]

With hybrid propulsion systems, you <u>start</u> with a non-catastrophic system! Effort may still be expended to maximize system reliability and therefore mission success, but the consequences of catastrophic failure associated with other propulsion systems are not present. Where crew safety is at stake, safe hybrid may be the only defensible technology for use in primary propulsion applications. [44]

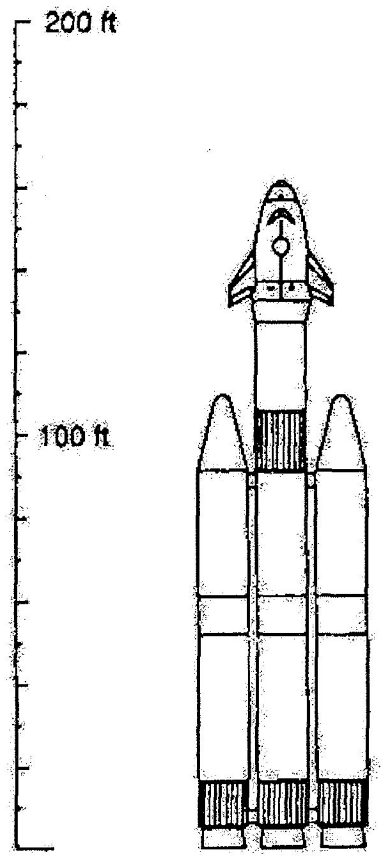
Based on the Personnel Launch System requirements shown below(Figure 33), a hybrid launcher was sized to get it to a low earth orbit. The system size was shown below in Figure 34, with specification in Figure 35.[44] Additional sizing was done with the same core vehicle to get the payload information shown in Figure 36.



Empty Weight	17,335 lb
Useful Load	3,370 lb
Propellant	4,067 lb
Gross Weight	24,772 lb
Abort/Escape System	9,770 lb

PLS Mass Summary

Figure 33 AMROC PLS Upper-Stage Vehicle[44]



PLS Launcher Configuration

Figure 34 AMROC PLS Launcher Configuration[44]

Booster Module (1st & 2nd Stage Motors)	
Propellant Weight	400,000 lb
Burnout Weight	65,100 lb
Takeoff Weight	465,100 lb
Average Isp (vac)	300 sec
Diameter	144 in
Length Overall	112 ft
Average Thrust (vac)	1,400,000 lbf
Third Stage	
Propellant Weight	100,000 lb
Burnout Weight	16,100 lb
Takeoff Weight	116,100 lb
Average Isp (vac)	322 sec
Diameter	144 in
Length Overall	34 ft
Average Thrust (vac)	168,000 lbf
Payload to 35 x 220 nm 28.5 deg. inclination orbit	25,300 lb
Gross Vehicle Takeoff Weight	1,536,700 lb

Figure 35 AMROC PLS Launcher System Sizing[44]

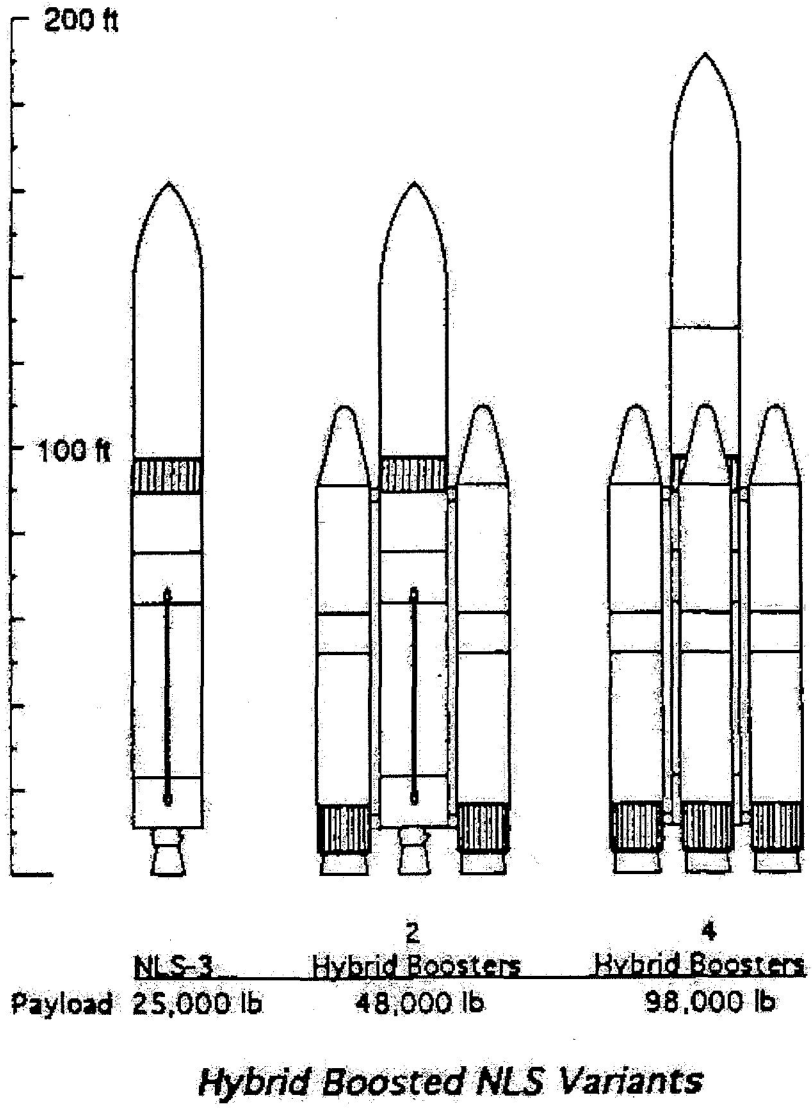


Figure 36 AMROC PLS Launcher System Sizing Payload[44]

Thiokol Strap-ons for Single Stage Vehicles

Many single stage to orbit (SSTO) and reusable launch vehicle (RLV) configurations were being evaluated as potential means of reducing payload delivery cost to low earth orbit (LEO) in 1994. Solid or hybrid boosters can provide thrust augmentation as a means to conveniently and economically increase the capability or reduce the overall size of a baseline SSTO vehicle to more effectively and economically capture the majority of the overall mission model. With this in mind, strap-on boosters (solid and hybrid) were designed to allow the basic size of the SSTO to be reduced to better target the high traffic portion of the mission model, and to also capture the larger payloads. Simple operational concepts for increasing the performance of the boosters were developed that are consistent with the rapid turn around philosophy of the SSTO vehicle.

Solid and hybrid propulsion were shown to have been an effective method of thrust augmentation for the SSTO mission.[45]

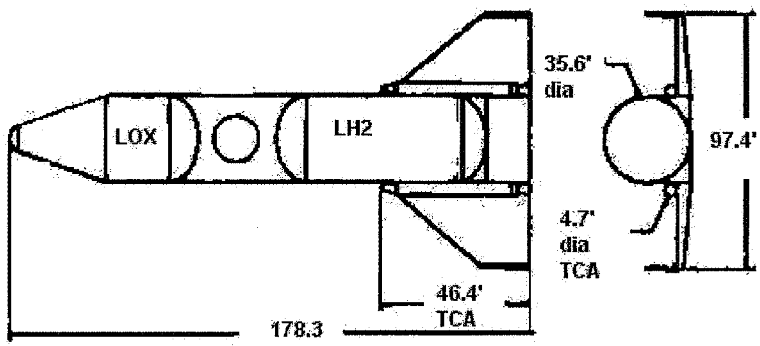


Figure 37 Thiokol Single Stage Vehicle with Strap-on Hybrids[45]

The solid and hybrid strap-ons were sized to increase the vehicle payload from 25,000 lb_m to 50,000.[45] The Hybrid strap-ons were feed from the vehicle main oxidizer tank and sized to:

Diameter (in)	56.0
Length (in)	599.3
Fuel weight (lb)	20,500.0
LOX Weight (lb)	52,500.0
TCA Weight (lb)	30,700.0
Total Weight (lb)	83,729.1
Mass Fraction	0.877
Average Vac Thrust (lb_f)	469,200
Specific Impulse (sec)	291.3
Total Impulse (lb_m-sec)	20,905,400.0
Burn Time (sec)	44.6
Average Mixture ratio	2.6
Average Pressure (psi)	1,002.0

The analysis showed the promise of hybrid strap-ons as a means to augment the booster launch capabilities.

Conclusions

The Firebolt was a hybrid rocket based supersonic target system that got thru production and development and was demonstrated with several successful flights propelling the vehicle to ~Mach 4, but did not get production funding for an operational system.

AMROC developed SET-1 as a suborbital launch system and the motor and other subsystems functioned well in component tests. However, on the brink of launching, but the vehicle didn't launch due to frozen condensation on the lox valve not allowing the LOX valve to fully open, keeping the motor on the pad. SET-1's unfortunate failure on the pad proved the safety of hybrids, damage to the test stand and payload were minimal. AMROC studied many hybrid rocket based concepts and were in development of the HyFlyer vehicle when they shut down.

The HPDP's nitrous oxide/HTPB based sounding rockets were successfully launched out of Wallops Island, with a maximum altitude of ~120,000 ft. It demonstrated quick turn around, safe non-pryogenic ignition and by recovering the rocket, the flight effect on the motor was the same as the ground testing.

Lockheed Martin's HYSR program's successful launch demonstrated several patented concepts that could be used on future hybrid systems. A staged combustion system was utilized for ignition and motor combustion stability. A heated helium pressurization system was employed for minimizing the weight of pressure fed propulsion systems by heating the ullage gas and pressurant tank. While the vehicle did not perform as well as predicted, the issues that caused the lower than expected performance were identified and can be corrected in future applications.

Hybrid rockets have been successfully propelled a privately financed manned vehicle to the edge of space in a historic series of flights - First privately funded rocket vehicle to break Mach 1, first privately funded vehicle to reach 62 nautical miles high, and then be able to do it twice in two weeks. Scaled Composite's selection of a nitrous oxide/HTPB based hybrid motor system for SpaceShipOne indicates that a hybrid motor's advantages of safety, simplicity and cost will be looked at again for larger, more complex systems.

Multiple studies have been done with hybrid rockets in the past. Replacing the Space Shuttle Solid Rocket Motors was looked at as an option. Strap-on replacements for expendable launch vehicles Atlas and Delta have been considered. Boost augmentation for proposed single stage to orbit vehicles have been examined. These studies all indicated that hybrids had some advantages for their vehicle configuration over the current strap-ons or other proposed strap-ons.

Hybrid based vehicles have been proposed, sized and studied for multiple payloads and applications – NLS and Next Generation Vehicle requirements. These studies showed some advantages over the proposed systems. These requirements were never met and systems were never produced.

However, there are new launch vehicles being proposed, where hybrids are potential players. Space Dev is studying hybrids for the Dream Chaser vehicle, Lockheed Martin was developing the Falcon vehicle for DARPA and the Air Force. NASA is currently investigating concepts for a Space Shuttle replacement – hybrids should be discussed if strap on rockets are needed.

Hybrid rocket motors have made limited progress into the world of launch vehicles due to the low technical maturity and flight history of hybrids prohibiting the investment into the necessary development. Recent demonstrations of hybrids have raised the technology readiness levels of hybrid rocket. Sizing studies have shown that hybrid launch vehicle or hybrid augmented vehicle could be developed and carry significant payload, if the technology is ready. The HYSR flight and the SpaceShipOne have advanced the maturity of hybrids, hopefully to the point of making hybrids a viable candidate for future vehicle systems.

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