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Upper-Stage Flight Experiment

W.E. Anderson, R. Boxwell, D.V. Crockett, R. Ross, and T. Lewis
Orbital Sciences Corporation, Launch Services Group
Chandler, AZ
C. McNeal
NASA Marshall Space Flight Center, AL
and
K. Verdarame
Air Force Research Lab/VS
Albuquerque, NM

Introduction

For propulsion applications that require that the propellants are storable for long periods, have a high density impulse, and are environmentally clean and non-toxic, the best choice is a combination of high-concentration hydrogen peroxide (High Test Peroxide, or HTP) and a liquid hydrocarbon (LHC) fuel. The HTP/LHC combination is suitable for low-cost launch vehicles, space taxi and space maneuvering vehicles, and kick stages.

Orbital Sciences Corporation is under contract with the NASA Marshall Space Flight Center in cooperation with the Air Force Research Lab to design, develop and demonstrate a new low-cost liquid upper stage based on HTP and JP-8. The Upper Stage Flight Experiment (USFE) focuses on key technologies necessary to demonstrate the operation of an inherently simple propulsion system with an innovative, state-of-the-art structure. Two key low-cost vehicle elements will be demonstrated – a 10,000 lbf thrust engine and an integrated composite tank structure.

The suborbital flight test of the USFE is scheduled for 2001. Preceding the flight tests are two major series of ground tests at NASA Stennis Space Center and a subscale tank development program to identify compatible composite materials and to verify their compatibility over long ~~time~~ periods of time. The ground tests include a thrust chamber development test series and an integrated stage test. This paper summarizes the results from the first phase of the thrust chamber development tests and the results to date from the tank material compatibility tests. Engine and tank configurations that meet the goals of the program are described.

Program Goals/Background/etc (Tim)

Could certainly use some stuff here

Structure and Tanks

Figure 1 shows the outline of the liquid upper stage. The stage consists of the integral structure, engine and propellant supply system, interstage, separation system, attitude control system (ACS), and the propellant pressurization system (PPS). Flow of propellant to the engine is by means of flexible lines from the propellant tanks that allow for thrust vector control by gimbaling the engine.

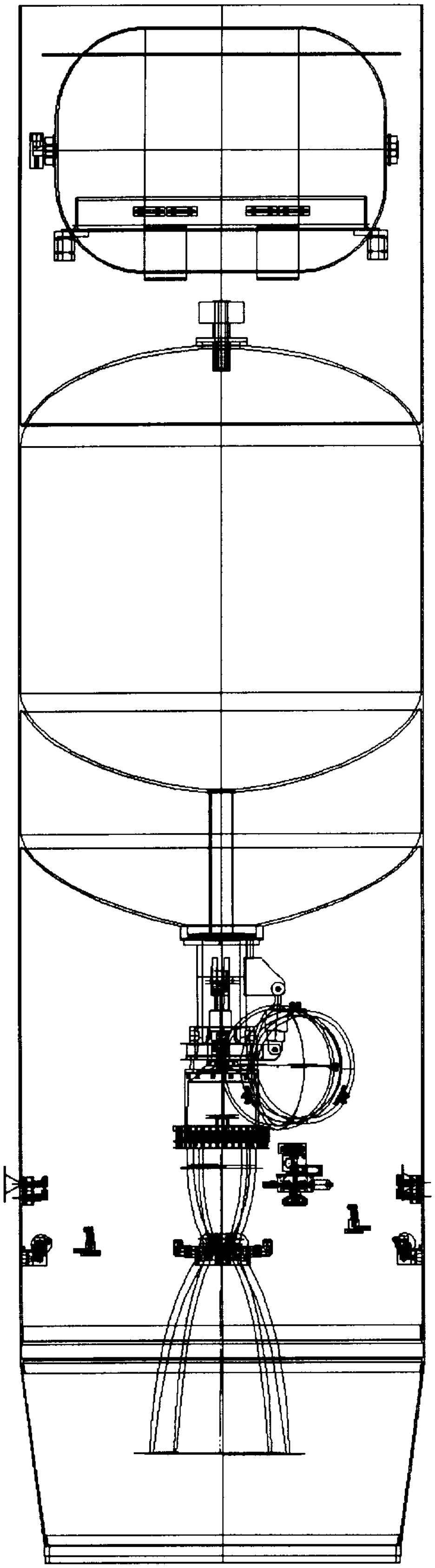

Fig. 1. Upper Stage Flight Experiment

The propellant pressurization system (PPS) is contained in the forward skirt of the integral structure. It consists of a 6000 psi carbon/epoxy plastic lined tank and assorted valves and pressure regulators. The working gas is helium. Besides providing flow pressure to drive the propellants through the thrust chamber assembly, the PPS also provides gas for purge, bipropellant valve actuation, and operation of the propellant management (PM) thrusters, which impulse-settle the propellants prior to engine start.

Maneuvering of the liquid upper stage ~~during satellite deployment~~ is accomplished through the onboard attitude control system, a cold gas system using nitrogen as the propellant. The ACS is located in the aft skirt of the integral structure. It consists of a 5000 psi kevlar/epoxy metal lined tank, assorted valves, regulator, and eight nozzles for pitch, yaw, and roll control.

Attachment of the USFE to the second stage is by means of the interstage and separation system. The interstage is a low-cost aluminum structure. A separation ring is used to mate the interstage to the liquid upper stage. Separation is accomplished by firing of a linear shape charge that will cut through the aluminum separation ring. Once the ring is cut, four sets of separation springs will push the interstage and attached lower second stage away from the USFE.

A unique aspect of the USFE is the integral structure. This structure is designed as a single-piece part incorporating the propellant tanks and the forward and aft skirts. Use of a common bulkhead to separate the fuel and oxidizer tanks allows for a reduction in stage volume and weight. By designing and fabricating the tanks and skirts as a single unit, the number of piece parts in the liquid upper stage are reduced. Significant reduction in the cost of the part is realized through the selected fabrication process. For low weight the structure is made of a carbon/epoxy material. A pressurized plastic liner is used as a mandrell for filament winding of both tanks to achieve low cost.

Prior to design and fabrication of the integral structure, the USFE program will go through a subscale tank development program to verify that certain key technologies are in place. Two different subscale tank configurations are utilized for this effort. The first tank configuration is taken from an existing tank design, thereby allowing use of existing tooling. This approach allows significant cost savings to the program and still serves to demonstrate certain technologies. The first tank configuration verified the ability to filament wind on a thermoplastic flouropolymer liner. It also demonstrated that the polar boss-to-liner mechanical seal is a zero leakage interface under pressure. Lastly this subscale tank has been storing HTP for the last seven months with minimal degradation in the peroxide. This first subscale tank has demonstrated the ability to build a pressurized propellant tank capable of storing HTP for periods up to a year.

The second subscale tank is a 40% scale model of the integral structure. Its purpose is to demonstrate development of an integral structure with an internal tank partition and attached skirts. This structure will utilize the same materials and boss interfaces as the first subscale tank.

Material Selection (Rich B.) Material selection is key to containment of the HTP. Material compatibility with HTP is classified sequentially from Class 1 materials, which exhibit virtually no reaction with hydrogen peroxide and can be used for long term storage, to Class 4 materials, which react strongly with hydrogen peroxide. One of the goals for the HTP tank was to prove the ability to store HTP in a flight-like tank for more than one year.

The first step in the development of the structure was to identify possible material candidates. This was accomplished through a three-phase material testing program. The first phase was designed for rapid screening of materials. This was done by means of a test to check for rapid decomposition of hydrogen peroxide as it came into contact with the candidate material. Materials passing this test generally fell in as a Class 1 or 2 material and then proceeded to Phase 2 testing. Phase 2 testing involved measurement of actual HTP decomposition as well as material degradation. This level of testing tended to segregate the Class 1 materials from the Class 2. Only those showing potential for Class 1 behavior were moved into Phase 3 testing.

In Phase 3 testing more accurate measurements are taken concerning HTP decomposition and material degradation. Testing involves both long term soaks and accelerated aging. One other aspect of phase 3 testing involves migration of organic compounds from the material into the HTP. Under extreme cases, the combination of these compounds with a strong oxidizer like HTP can produce an explosive or detonable mixture, and obviously must be avoided. To date Orbital has identified several Class 1 materials applicable for use in a composite storage tank. Both the liner and the epoxy used in the composite overwrap will be Class 1 materials. The stainless steel polar bosses used in the tank are passivated to level that makes them a Class 1 material. To achieve this level of HTP compatibility, Orbital has conducted a study to determine the optimum level of passivation.

Further validation of the HTP tank design is ongoing through subscale tank development. The subscale tanks will be used to first verify the polar boss/liner seal design and then to verify the ability to store HTP for long periods of time.

Hydrogen Peroxide/JP-8 Engine

The engine consists of pneumatically-actuated ball valves, propellant feed-lines, the oxidizer dome with a mount for gimbal attachments, a catalyst bed to convert the HTP into oxygen and superheated steam, a fuel injector, and an ablative chamber and nozzle. Low material and design costs coupled with robust margins were the guiding philosophy toward selecting a design.

The engine design and operating parameters are provided in Table 1. The engine develops 10,000 lbf of thrust at vacuum conditions with a 40:1 expansion ratio nozzle. Chamber pressure was chosen to be 500 psia, which spans the operating regimes of pressure-fed and pump-fed systems. Based on a demonstrated C* efficiency of 0.97 and an assumed nozzle efficiency of 0.98, the delivered vacuum specific impulse is 294 s at a mixture ratio of 6.0.

Parameter	Value
Propellants	85% HTP/JP-8
Vacuum Thrust, lbf	10,000
Chamber Pressure, psia	500
Mixture Ratio	6.0
Nozzle Expansion Ratio	40 (five for ground tests)
Chamber Contraction Ratio	7.1
Delivered Specific Impulse, s	278
Flowrate, lb/s	36.0
Burn Time, s	200
Engine Envelope	60 in. long, 40 in. diameter

Table 1. Design and Operating Parameters of USFE Engine

The catalyst, injector, and ablative chamber designs are based on the results from two sets of subscale tests which used a 50 lbf monopropellant thruster for catalyst bed screening and a subscale bipropellant thrust chamber for injector development tests.[1, 2] The subscale configuration captured key design features of the fullscale catalyst bed, the injector and the chamber.

Historical designs were used to size the TCA (Fig. 2).[3] To ensure autoignition of the fuel, a contraction ratio of about seven was chosen. The resulting chamber inner diameter was ten inches. Maintaining this inner diameter in the catalyst bed led to a bed mass flux, or *G*, the loading parameter, of 0.4 lb/s-in^2, which is also within the historical operating range of silver screen-based catalyst beds.

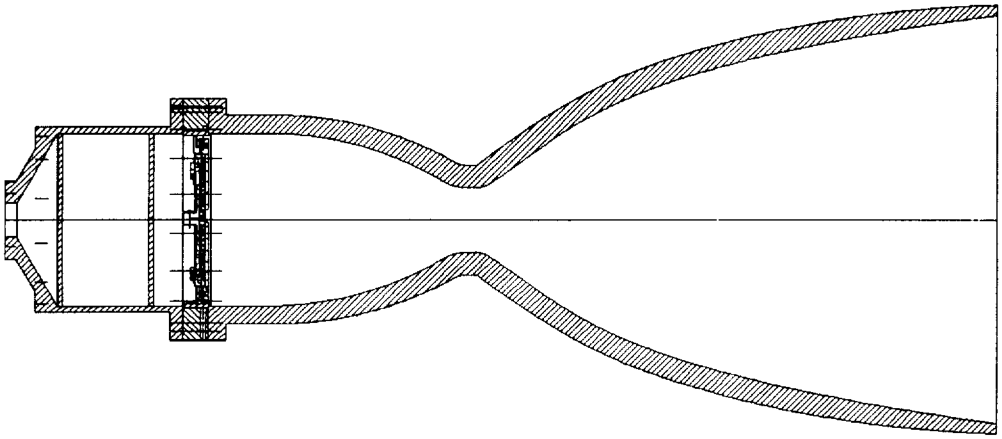

Fig. 2. USFE Thrust Chamber Assembly. TCA consists of oxidizer dome, catalyst bed assembly, fuel injector, and ablative chamber/nozzle. Chamber inner diameter is 10 in, throat diameter is 3.74 in, and nozzle exit diameter is 23.7 in.

Test Facility Description

Full scale tests were conducted at the E-3 Test Cell at NASA Stennis Space Center (see Fig. 3). The E-3 Test Facility is a versatile two-cell test complex for component development testing of

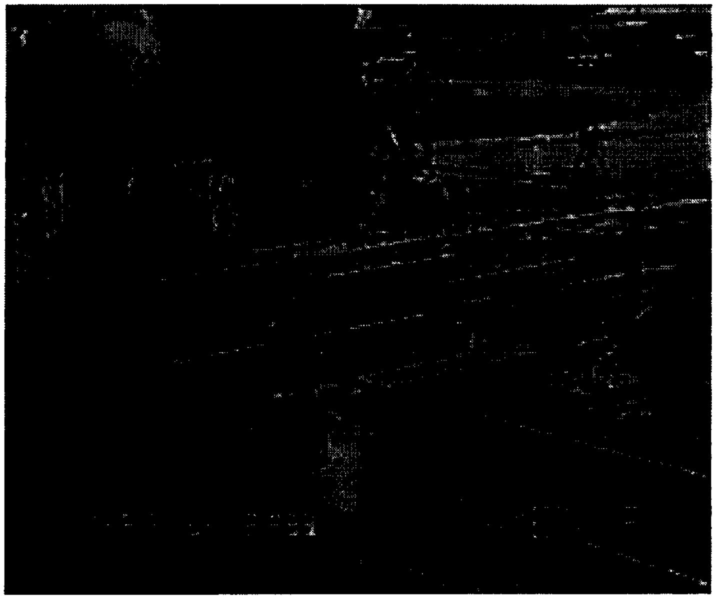

Fig. 3. Thrust Chamber Testing of USFE at E-3 Test Cell at Stennis Space Center. Chamber produces approximately 8000 lb_f of thrust at sea level with a 5:1 nozzle expansion.

combustion devices, rocket engine components and small/subscale complete engines and boosters. Cell 2 features a skid-based design concept in a vertical-fire configuration. In this concept all test specific hardware (run tanks, run lines, and test article) are mounted to a platform that is bolted above the existing 8 ft. wide by 17 ft. deep concrete flame bucket. The existing platform contains a 500 gallon oxidizer run tank and a 250 gallon fuel run tank. At the nominal flow, a maximum run duration of 140 s was possible. Downstream of the tanks in both the fuel and oxidizer lines were instrumented run lines including isolation valves, turbine flowmeters, flow control valves, purge line inlets, cavitating venturis, and test article interface flanges. The platform includes a 48 in by 48 in flame bucket access hole aligned with the test article.

Two vertical thrust takeout structures can be mounted above the flame bucket access hole. One is outfitted with the single axis thrust measurement system (TMS), whereas the other is shorter and stiffer but does not have TMS capability. An isolated area surrounded by a 2 ft. high earthen berm is located east of the test cells for the storage of HTP. A 4,500 gallon trailer-mounted storage tank provided by Solvay Interox was positioned next to the test skid during propellant loading operations.

The E3 Test Control Center (TCC), located in the E-Complex Test Operations Building houses control system (CS) equipment, and serves as the central command location for the test conductor and test personnel during test operations. The CS is a PC and National Instruments (NI) based system that provides control of the facility, pretest setup, run-time displays, automated facility monitoring, and shutdown. The system provides real-time control of the test article coolant, propellants and valve schedules.

Facility instrumentation provides real-time display of facility processes and data recording. The facility also provides the ability to display real-time test article measurements. The low speed data acquisition system (LSDAS) can accept up to 80 analog input channels for a total throughput of 1,200 sps of 12 bit data. The LSDAS provides a real-time display with a refresh rate of 15 cycles per second. Real-time calculated value capability is available. The high speed data acquisition system (HSDAS) provides 20 analog input channels with a throughput of up to 80,000 sps per channel of 16 bit data. One channel is presently reserved for IRIG B time recording. The data is recorded digitally on Super VHS tape. Data processing was provided for the LSDAS and HSDAS. The LSDAS data was converted to Engineering Units and processed into a standard file format utilized in the E-complex. The HSDAS data was filtered and processed to Fast Fourier Transforms (FFT) for frequency analysis.

Test Results

The full-scale tests consisted of four distinct test series:

- monopropellant tests to verify test operations and the performance of the catalyst bed
- short duration tests in a copper heat-sink chamber to verify injector performance

- longer duration tests with an ablative chamber to characterize the ablation characteristics of the injector/chamber combination
- a long duration test (140 s) that simulates the total burn time of the actual mission.

Over 100 tests were conducted. The general test objectives were to demonstrate the performance and life of the thrust chamber assembly, including catalyst bed, injector, and ablative chamber, and to demonstrate safe operations with hydrogen peroxide. Component development success criteria were: 95% conversion efficiency in the catalyst bed (as determined from monopropellant C* measurements); greater than 95% bipropellant C* efficiency; and throat erosion rates less than 0.001 in/s. All these criteria were exceeded in the full scale tests. All operations were conducted safely with no significant incidents or lost-time accidents. Some of the test highlights were:

- conducted 102 tests
- accumulated over 28 minutes of test time
- accumulated over 300 seconds of bipropellant operation using ablative chambers
- accumulated over 700 seconds of run time on GK cat bed without performance degradation
- demonstrated throat recession rates of less than 0.001 in/s at O/F=6
- demonstrated C* efficiencies greater than 0.97
- tested nine different test article configurations
- tested two different peroxide batches showing performance differences
- demonstrated multiple restarts
- demonstrated throttling to 10% in monoprop mode and to 20% in biprop mode
- maintained perfect safety record

The demonstration test thrust chamber assembly (TCA) was designed in a bolted-together arrangement to allow for rapid component replacement. The TCA consisted of four distinct subcomponents: a workhorse oxidizer dome with a side inlet which served as a test facility interface; a catalyst bed assembly, including a structural housing and a slip-in catalyst bed to allow different cat bed designs to be tested; a fuel manifold (another test facility interface) and injector; and the chamber/nozzle.

Two different chamber/nozzle configurations were tested – a copper heat sink chamber and an ablative chamber. The heat sink chamber was well-instrumented for making pressure and temperature measurements. Static pressure measurements were made in three axial locations – near the injector face, at the entrance to the converging part of the chamber, and in the chamber throat. A water-cooled high-speed pressure transducer was placed one inch downstream of the injector face. Linear array thermocouples were inserted into the chamber to measure heat flux at four different locations. The heat flux measurements were used to determine the near wall gas temperature, which in turn was used in conjunction with the CMA code to predict the operating O/F that would result in an acceptable amount of throat erosion in the ablative chamber.

The catalyst beds tested were essentially of the silver screen type. Both pure silver and silver-plated nickel screen catalysts were tested. Both uncoated and coated screens were tested. The best configuration tested was made of pure silver screens with a samarium nitrate coating. The bed length was two inches. The nominal bed loading was 0.4 $lb/s\text{-}in^2$, and values up to 0.7 were tested. At this high value of G, high decomposition temperatures were measured, but the exhaust plume observed by remote cameras was not transparent like it was for the nominal case.

Catalyst bed performance was determined by comparing pressure and temperature measurements with pressures and decomposition gas temperatures predicted by a chemical equilibrium code. Pressure and temperature were measured at a location between the cat bed exit and the injector entrance. Whenever the exhaust plume was clear, the measurements indicated essentially 100% decomposition.

Two types of injectors were tested – a "steam port" design, similar to that used in the Gamma engines, and the other a ring-type injector. The injectors are shown in Fig. 4. The outer diameter of the injectors are oversized to accommodate the large outer diameter of the heat sink chamber. The ring injector used O/F biasing to provide a fuel-rich gas around the chamber periphery, and near stoichiometric conditions in the core. Injector performance was determined from chamber pressure measurements and comparison with theoretical C* values. The pressure loss across the injector was also measured. Both injectors achieved

C* efficiencies greater than 95% at their nominal operating conditions (Fig. 5). A higher operating O/F was possible with the ring injector because the fuel-rich periphery provided for minimal throat erosion.

The ablative chamber/nozzle consists of a silica phenolic liner and an epoxy-glass phenolic overwrap, and was manufactured by American Automated Engineering. For sea-level tests, the 40:1 nozzle is cut at a 5:1 ratio, providing a nearly ideal expansion to atmospheric conditions. The ablative chamber was instrumented with thermocouples and strain gages.

The throat erosion was measured after each test with calipers. The rate of erosion was determined to be a function of operating O/F and the injector used. ***Robert – can you finish this off with a description of the analysis process and a figure that summarizes the effort?***

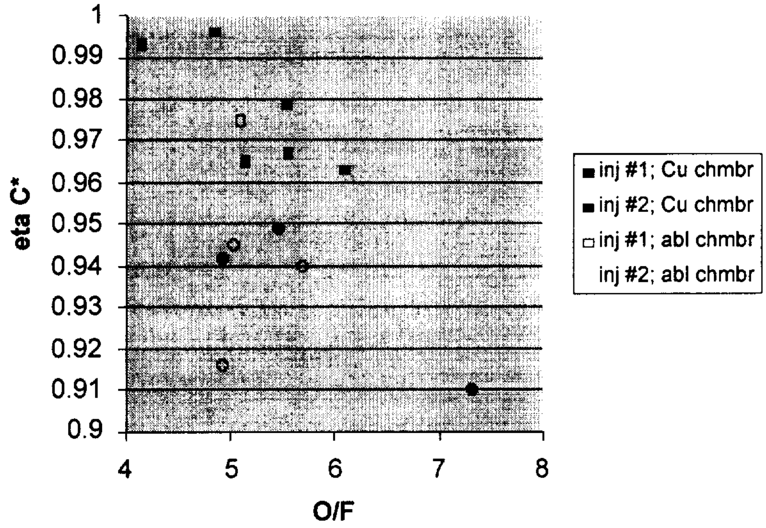

Fig. 5. C* Efficiency as function of O/F in heat sink (Cu) and ablative (abl) chambers. Injector # 1 is "steam port" design and injector #2 is ring design.

Summary and Conclusions

In 2000, an integrated stage ground test will be conducted at Stennis. For this test, the complete engine will be integrated with the thrust vector control, the flight tanks, and the flight engine controller. A simulated flight mission will be the test.

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References