LOW COST PROPULSION USING
A HIGH-DENSITY, STORABLE, AND CLEAN PROPELLANT COMBINATION

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Abstract

Opportunities exist for the development of very low cost rocket propulsion systems. The demonstration of certain key technologies that allow dramatic reductions in system complexity as well as significant improvements in production and ground operations is a necessary first step in the process. The Upper Stage Flight Experiment (USFE) focuses on the key technologies necessary to demonstrate the ability to fly a low-cost system through the use of an inherently simple propulsion system coupled with an innovative, state-of-the-art structure. This paper outlines the USFE program objectives and describes the work being conducted under the program.

Introduction

A variety of factors have resulted in increasing interest in the exploration of alternatives to the widely employed cryogenic and hypergolic propellant combinations. These factors include heightened sensitivity to cost, environmental concerns, and the personnel hazards associated with toxic propellants. Further driving the move toward other propellants is the realization that absolute performance in terms of specific impulse is not, for many applications, the most appropriate metric for selecting a propulsion system. Recent advances in material, structural, and manufacturing technologies allow the system designer the flexibility to employ nontraditional propellant combinations to develop an extremely low cost, commercially feasible system.

NASA and Air Force studies have indicated that in order to achieve significant reductions in cost, future launch and space systems require specific and significant improvements in technology and design-to-cost methodologies. Some of the system studies have shown that in order to achieve commercial viability, reusable launch vehicle concepts require low cost transfer stage systems. These systems must be nontoxic, storable, restartable and throttleable, and must have a high density impulse. The propellant combination of high- concentration hydrogen peroxide and a liquid hydrocarbon fuel meets these requirements.

The Upper Stage Flight Experiment (USFE) program was put in place to develop the fundamental building blocks through flight demonstration of two key technologies: a hydrogen peroxide -based engine and an integral composite tank and stage structure. This paper describes the benefits of hydrogen peroxide as a propellant, reviews the USFE program objectives, provides a vehicle description, and discusses the vehicle structure and engine.

Background

The choice of the propellant combination is made early during the system requirement phase. For absolutely lowest operations costs in rapid turnaround, launch-on-demand applications, a propellant combination that is storable and environmentally clean must be considered. Hydrogen peroxide, which has been generally dismissed because it does not have the performance attributes of liquid oxygen (LOX) or hydrazine (like hydrogen peroxide, a monopropellant), has these key features as well as others which make it an ideal choice for a low-cost propulsion system.

A number of features and benefits of high-concentration hydrogen peroxide (high-test peroxide, or HTP) as a propellant are provided in Table 1. First, HTP is a storable, nontoxic propellant. Propellants that can be stored at normal ambient conditions simplify ground operations and reduce the costs related to propellant handling. They can be loaded onto a vehicle without extraordinary procedures or insulation on the vehicle. Tankage, plumbing, and other related structures are simpler and more efficient. The specialized and expensive hardware required by cryogenic propellants are eliminated. Hydrogen peroxide allows the use of commercial, off-the-shelf hardware in many instances.

Hydrogen peroxide can be stored for periods well over a year at ambient conditions in lined storage tanks or tanks made of high-purity aluminum. For feed lines and valves, 300-series stainless steel is typically used. Standard sealing materials, such as Teflon and Viton, are used. Cleaning procedures are well-known and simple compared to the extremely stringent procedures necessary with LOX. Since HTP is nontoxic and its decomposition products are nonpolluting, the specialized operational procedures needed to deal with toxic and polluting

Features	Benefits
Non-toxic and storable	Commercial, off-the-shelf valves, sensors, etc. Easier propellant packaging and no insulation Simplified ground operations
Favorable thermo-chemistry	Relatively benign oxidizer Very high density impulse Simpler thermal management
Oxidizer/ monopropel-lant	No separate ignition systems required High range of thrust variation Smoother starts and shutdowns Low-cost pump-fed systems
Gas-liquid injection	Increased stability margin Higher combustion efficiency Simpler injection design
Developed technology	Low-cost development

Table 1. Features and Benefits of Using Hydrogen Peroxide as a Propellant

propellants are replaced with streamlined, commercially-based procedures. Contrary to anecdotal reports, HTP can be used safely even under severely adverse conditions.[1]

Hydrogen peroxide is a relatively mild oxidizer that has the unique feature that it can also be used as a monopropellant by using a catalyst bed to promote decomposition to a mixture of steam and oxygen. It has a long history of use in rocket systems at concentration levels between about 70 and 100%. The thermochemistry of HTP is ideal for incorporating long life and maintainability into the design by reducing the severe thermal and mechanical environments that shorten component life. The temperature gradient near the critical combustor entrance region is about 35% less for a HTP/hydrocarbon propellant combination than it is for LOX/RP-1 propellants, providing a more benign thermal environment for extended life and simpler designs. The peroxide is also a very good coolant, with properties very similar to water; this and the fact that there is an abundance of HTP for cooling opens the possibilities of low-cost, regeneratively- or film-cooled thrust chambers for high-pressure applications. The use of HTP in conjunction with a clean-burning fuel allows the development of injectors and thrust chambers with a long-life and reduced maintenance requirements.

In most propulsion systems using HTP, catalyst beds are used to promote the decomposition of HTP into a hot gas mixture of superheated steam and oxygen. The decomposition gas properties for 90% HTP are given in Table 2. Since the adiabatic decomposition temperature is above the autoignition temperature of typical hydrocarbon fuels, combustion occurs spontaneously when fuel is added and an ignition system is not necessary. In addition to deleting the ignition system, by tapping the hot gas off the main chamber downstream of the catalyst bed, the gas generator subsystem can also be removed.

Since HTP can be used as both an oxidizer and a monopropellant, a number of beneficial design simplifications and variable operational scenarios are possible. The decomposition products can be used as the oxidizer in a bipropellant system, for thrust in monopropellant mode, and as the working fluid for pressurization and turbine drive. The dual mode operation (mono- or bipropellant) enables wide thrust variability.

One of the more costly components of a new propulsion system is the development of the thrust chamber assembly. Besides the cost savings due to the less severe thermo-structural requirements described above, simple and scaleable gas-liquid injection systems, that yield higher combustion efficiencies and greater margins from combustion in-

Adiabatic Decomposition Temperature	1365 ° F
Molecular Weight	22.1 lb/lb-moles
Ratio of Specific Heats (γ)	1.26
Vacuum Specific Impulse	175 s
H_2O/O_2 by Weight	58/42

Table 2. Decomposition Properties of 90% Hydrogen Peroxide

stability than liquid-liquid injection systems, can be used with essentially any liquid fuel. The simplicity of the thrust chamber design should help reduce development costs.

Relative development costs should also be low because of the relatively mature state of technology indicated by numerous operational systems of the past. In addition to many conventional gas generator and reaction control systems, notable main-stage operational systems include various military applications used by Germany during World War II;[1] the Black Knight ballistic missile program, in which 22 launches were made during the 1950's and 60's and which culminated in a launch of the Prospero satellite on a three-stage peroxide-based vehicle in 1972;[2] and manned aircraft applications in the U.K.[3] and the U.S.[4] Because of the huge technology base provided by the non-propulsion uses of hydrogen peroxide, development costs of future HTP-based propulsion and ground operations systems can be minimized.

The performance characteristics of HTP/JP-4 are given and compared with the liquid oxygen/kerosene (LOX/RP-1) and nitrogen tetroxide/monomethyl hydrazine (NTO/MMH) propellant combinations in Fig. 1. Vacuum specific impulse and density impulse values predicted from the Two-Dimensional Kinetics (TDK) program are given for a chamber pressure of 500 psia and expansion ratio of 20. Density impulse is a measure of the total impulse delivered per unit volume of the propellant, and is the product of the specific impulse and the specific weight of the propellant combination, where the specific weight, d, is defined as:

$$d = (MR+1) \Big/ \left(\frac{MR}{d_o} + \frac{1}{d_f} \right)$$

where MR is the mixture ratio (O/F), and d_o and d_f are the oxidizer and fuel specific weights. The high density impulse values of HTP, along with its storability, make the propellant combination a prime candidate for applications where size is a major factor.

Upper Stage Flight Engine Program Status

General Objectives

Orbital Sciences has been awarded a contract by the NASA Marshall Space Flight Center in cooperation with the Air Force Research Lab Technology Program Office to design, develop and qualify a new low-cost liquid upper stage. For this program, Orbital will demonstrate two key low-cost launch vehicle components: the bipropellant upper stage engine and an integrated composite tank structure. Once these components have been developed and demonstrated in ground tests, the new liquid upper stage will be integrated and flight tested as a third stage to the first two stages of the Minuteman II

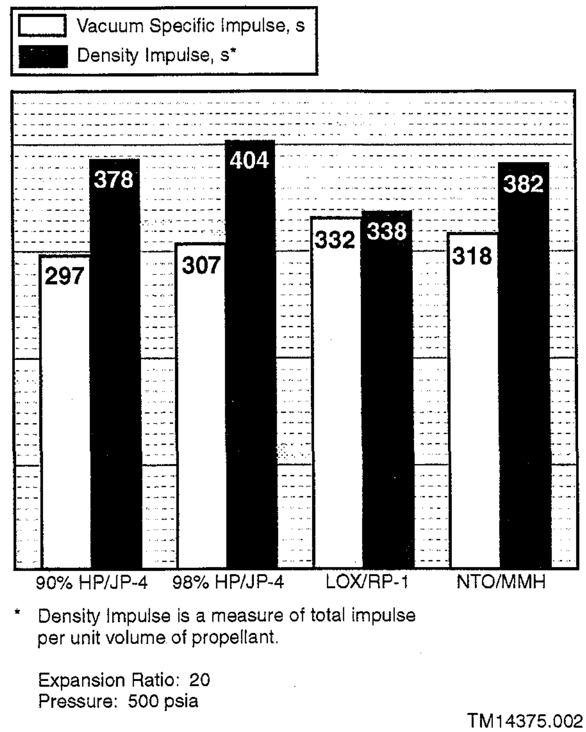

Figure 1. Propellant Comparison Indicates That H_2O_2/JP-4 Provides Best Performance For Volume Limited Application

Launch Vehicle (M55 and SR-19). The orbital rocket is scheduled to be launched in early 2000 from Kodiak Island in Alaska.

The USFE trajectory was shaped to be a maximum range trajectory (no trajectory requirements exist) for the highest-weight vehicle. The trajectory has an apogee of 563 km with a range of 2800 km (see Fig. 2). The USFE stage is boosted to an ignition flight condition of 167 km altitude and 2650 m/sec velocity. This is done using the OSP (Minuteman II) stage 1 (M55) and stage 2 (SR19) solid rocket motors. The 61-second stage 1 burn is followed by stage separation and by a 66-second stage 2 burn. The expended stage 2 is separated shortly after burn out and the USFE stage starts a cold gas blow down to provide a small amount of axial acceleration for propellant management. The USFE stage is then ignited and burns for 100 seconds. After a 30-second coast, the propellant valves are commanded open, and a second 100-second burn is started to demonstrate restart capability. The mission is completed at the end of the second burn.

Vehicle Outline

Figure 3 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

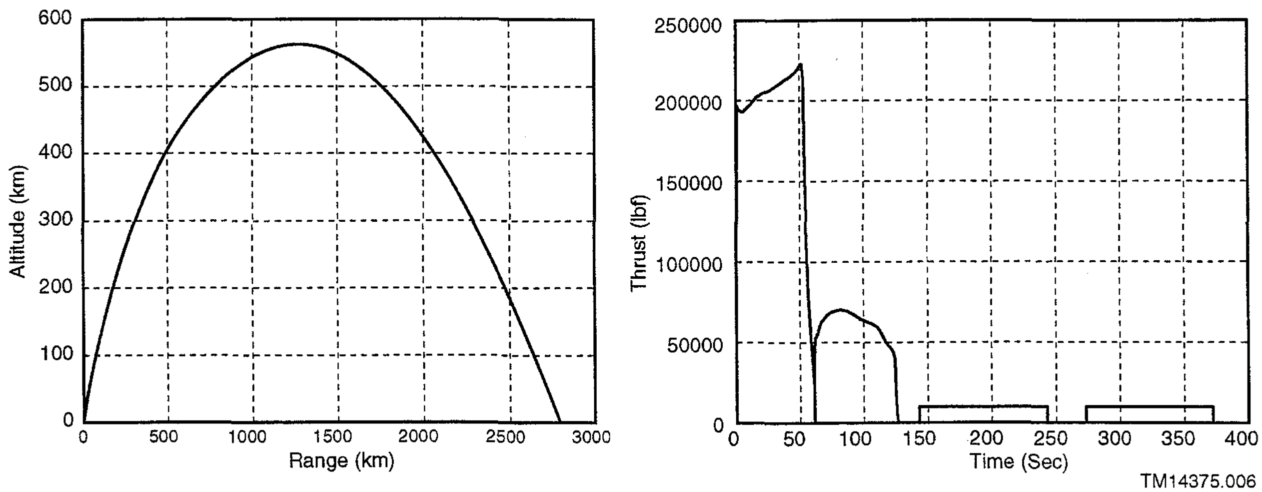

Figure 2. Upper Stage Flight Experiment Trajectory

from the propellant tanks. These flexible lines allow for gimbaling of the engine.

The propellant pressurization system is contained in the forward skirt of the integral structure. It consists of a large volume 6000 psi carbon/epoxy plastic lined tank and assorted valves and pressure regulator. The working gas is helium. Besides providing flow pressure to drive the propellants through the thrust chamber assembly, the PPS also provides gas for purging of the engine, bipropellant valve actuation, and operation of the propellant management (PM) thrusters. Since no propellant management device is used within in the propellant tanks (i.e., bladder or surface tension device), cold gas thrusters are used to settle the propellant prior to engine start. Two PM thrusters are located in the aft skirt are used.

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.

Propellant Tanks

A unique aspect of the USFE is the integral structure. This structure is designed as a single-piece part incorporating all of the propellant tankage 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 tankage 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 light weight the structure is made of a carbon/epoxy with a plastic liner for the hydrogen peroxide tank. No liner is used in the JP-8 tank. To achieve low cost, fabrication of the structure is done using a filament winding process.

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, 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 for greater than one year, which requires the use of Class 1 materials. 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.

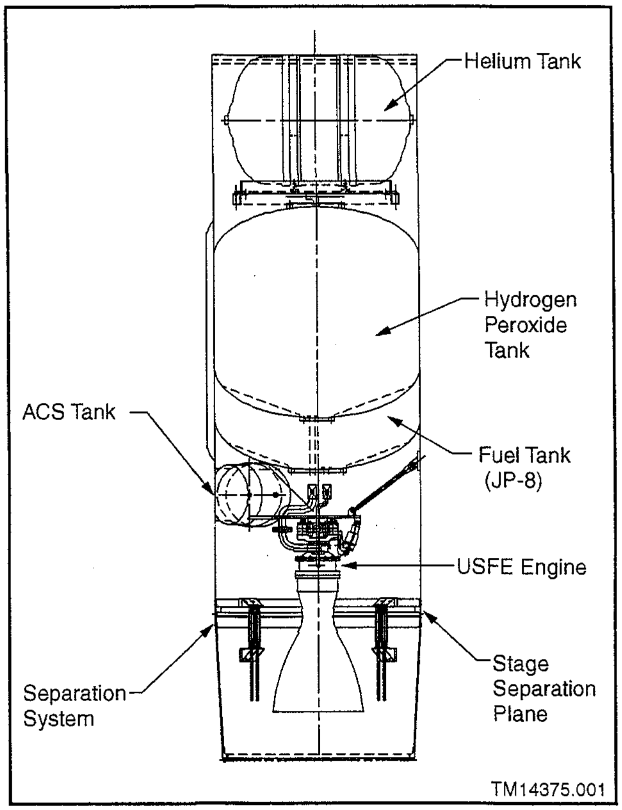

Figure 3. Upper Stage Flight Experiment

In phase 3 testing more accurate measurements are taken concerning HTP decomposition and material degradation. Testing involves both longer 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. One of the materials will be used as a liner. The epoxy used in the composite overwrap is also shown to be a Class 1 material so that if there is a leak in the composite liner, HTP will be contained by composite overwrap.

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 passivation study program in order to determine the optimum level of passivation.

Validation of the HTP tank design will be done through subscale tank development. This is currently on going. 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. The integrity of the polar boss/liner seal is done prior to winding of the composite overwrap.

Engine Overview

The engine consists of pneumatically-actuated ball valves, propellant feed-lines, the oxidizer dome with a mount for gimbal attachments, a catalyst bed made of silver-plated nickel screens, a fuel injector, and an ablative chamber and nozzle. Low material and design costs coupled with robust design margins were the guiding philosophy toward selecting a design.

The engine design and operating parameters are provided in Table 3. The engine develops 10,000 lb of force at vacuum conditions with a 40:1 expansion ratio nozzle. Chamber pressure was chosen to be 500 psia. Based on an energy release efficiency of 0.95, the specific impulse is 294 s at a mixture ratio of 7.0.

The valves are commercial, off-the-shelf, ball valves compatible with HTP. They are designed to provide a "soft" open and close sequence, and are vented to eliminate any trapping of HTP behind the ball when it is closed. Prior to installation, the valves will be passivated using the procedure developed during Orbital's passivation study. The valves will use a downstream purge, and oxidizer leads and lags will be used during the start and shutdown sequences. Because the valves are commercial items, environmental tests will be conducted at Orbital to qualify their use at the shock and vibration levels expected during flight.

The catalyst, injector, and chamber designs are based on the results from two sets of subscale tests. The subscale tests used a 50 lbf monopropellant thruster for catalyst bed development and a 1000 lbf engine for bipropellant tests. The objectives of the 50 lbf monopropellant tests were to demonstrate the achievable propellant flux through the catalyst bed at high decomposition efficiencies (decomposition efficiency required to be > 0.95), the catalyst bed lifetime (required to be > 400 s), and pressure drop across the catalyst bed (required to be < 100 psid).

The 1000 lbf engine is a scaled version of the fullscale engine that captures key design features of the injector and chamber. The specific objectives of the 1K engine tests are:

- determine scalability of the catalyst bed design
- demonstrate thrust efficiency goals
- determine chamber length
- demonstrate stable combustion
- determine ablative char rate
- determine chamber and throat erosion characteristics
- demonstrate safe and reliable startup and shutdown

Parameter	Value
Propellants	85% HTP/JP-8
Vacuum thrust, lbf	10,000
Chamber pressure, psia	500
Mixture ratio	TBD for best performance (7.0 nominal)
Nozzle expansion ratio	40
Chamber contraction ratio	7.0
Specific impulse, s	294 (based on 0.95 thrust efficiency)
Flowrate, lb/s	34
Supply pressure, psia	650
Chamber lifetime, s	200
Engine envelope	60 in long, 40 in diameter

Table 3. Design and Operating Parameters of USFE Engine

- establish engine purge requirements
- demonstrate thermal management of injector face
- determine fuel film cooling requirements
- validate chamber attach ring and seal thermal management

Subscale Engine Test Facility

The subscale chambers were tested at the Aero Thermal Laboratory at Kaiser Marquardt. The test facility includes run tanks for hydrogen peroxide and JP-8 fuel, a propellant delivery system, a thrust stand, a PC data acquisition system, and a system operation control. These components will be discussed in the following sections.

Propellant Run Tanks

The run tanks for hydrogen peroxide included 30-gallon and 45-gallon stainless steel tanks, while a 100-gallon stainless steel tank was used for JP-8 fuel. The large propellant tank volume was required for engine life testing. These tanks were hydrostatically tested to 1500 psia and were acid cleaned to remove rust and residual chemicals. The tanks were instrumented to measure propellant pressure and temperature. Gaseous helium from commercial bottles was used as the pressurization agent for both propellants.

Hydrogen peroxide and JP-8 fuel are delivered to the engine through a propellant delivery system. The system includes a feed line for hydrogen peroxide and two fuel feed lines for the fuel. Two feed lines were used so that the mass flow rates for the primary and fuel film cooling fuel manifolds can be independently controlled. All feed lines utilize pneumatically controlled solenoid valves to control propellant flow rates, which were measured by turbine flow meters. Gaseous nitrogen and helium were used as the purge gas for JP-8 and H_2O_2, respectively. Check valves were installed at appropriate locations to prevent back flow of propellants.

A thrust stand was used to measure the thrust of the subscale engine. The thrust stand was mounted to the ground and was rated for more than 10,000 lbf. The engine was installed to the top structure of the stand, which can slide along the thrust direction. Load cells were used to measure the displacement caused by the thrust.

Engine control, data acquisition, and on-line performance analysis is performed using a PC-based system. The system is composed of an Intel 333-MHz Pentium II microprocessor operating in conjunction with an Iotech multifunction I/O board, signal conditioning equipment, and channel multiplexing modules. A 16-bit analog-to-digital (A/D) converter, capable of up to a 100-kHz sampling rate, is at the heart of the data acquisitions system. Several add-on channel multiplexing modules provide signal conditioning for pressure transducers, load cells, thermocouples, turbine flowmeters, and other general measurement devices. The current system can handle a combination of up to 16 pressure transducers and load cells, 14 thermocouples, four turbine flow meters, and eight general voltage inputs. The system can be expanded to handle a total of up to 256 inputs. An additional module provides 24 optically isolated digital outputs, each capable of switching up to 60 VDC at 1 amp. Two of these outputs currently provide control over the engine solenoid valves. The DASYLab+ software was used to create an integrated engine control, data acquisition, and on-line analysis system with a Windows95-based graphical user interface. Algebraic relations developed from curve fits of theoretical performance data allow for on-line and *in situ* performance analysis. Each cycle of data is reduced instantly and calculated performance parameters are immediately displayed with continual update. A 21" color monitor, operating in high-resolution mode, allows for simultaneous display of all measured data, reduced parameters, virtual strip chart recordings, point-and-click engine controls, and engine firing status.

Temperature measurements are obtained using standard type-K thermocouples. This includes measurement of both the oxidizer and fuel temperatures at respective engine inlet manifolds, the temperature of the decomposed products exiting the catalyst bed, and the wall temperature at the throat of the combustion chamber.

Static pressure measurements are obtained using standard strain-gage type pressure transducers. This includes propellant inlet pressures, oxidizer pressure upstream and downstream of the catalyst bed, and five independent chamber pressures at different axial locations.

Dynamic pressures are obtained using piezoelectric type pressure transducers. This includes measurement of the propellant pressure fluctuations at the engine inlets and chamber pressure fluctuation at the midway point of the combustion chamber.

Propellant flow rate measurements are obtained using standard turbine flow meters with electromagnetic pickups. This includes measurements of both the primary and film-cooling fuel flow rates as well as the oxidizer flow rate.

Heat flux measurements are obtained using Gardon heat flux gages. Heat flux measurements are taken at the combustion chamber wall near the fuel injector face and midway along the combustion chamber.

Thrust is measured using standard strain-gage type load cells. Two load cells are installed, one as a calibration load cell operating in tension and the other as the measuring load cell operating in compression. The measuring load cell provides two independent outputs.

Finally, an accelerometer is mounted on the engine to provide measurements of the maximum g-loading and to identify any incipient or sustained modes of instability.

<u>System Operation</u>

Once the facility has been prepared for operation, firing of the 1000-lbf, subscale engine is relatively simple. Prior to hot-fire, the propellant tanks are pressurized to the required levels. The control pressure for the propellant valves are then adjusted to obtain the required initial flow rates when the valves are opened. The prescribed duration of bipropellant hot-fire, which is controlled by the computer system, is entered by the engine operator. The data acquisition system is then activated and all measurements are checked for consistency. After all checks have been made, the oxidizer valve is opened first and the engine begins operation in monopropellant mode. Depending on the initial conditions of the catalyst bed, the engine may be started by establishing the oxidizer flow rate through either a gradual increase or a sudden impulse. After the flow of oxidizer has been established, the catalyst bed loading, characteristic velocity, and decomposition temperature rise are calculated *in situ* to determine engine performance. These parameters are compared to the theoretical values to determine decomposition efficiency. After the efficiency has reached a prescribed minimum, the operator may initiate bipropellant mode by opening the fuel valve and thus firing the engine at will. The fuel valve will remain open for a prescribed amount of time, after which, the computer will automatically shut down the engine (termination of both oxidizer and fuel) and recycle for the next run. Post analysis on the recorded data is then performed and time traces of pressures, temperatures, flow rates, thrust, and efficiencies are generated. All data may be quickly analyzed prior to the next run.

<u>Mono-Propellant Mode Testing</u>

The monopropellant mode testing was conducted to evaluate the performance of different catalyst bed designs in an effort to provide a reliable catalyst for H_2O_2 decomposition. The evaluation was performed at two different bed diameter levels. A 50-lbf monopropellant engine with a 1.0 inch diameter was used to determine the optimal catalyst bed configuration and the subscale engine with a 3.5 inch diameter was used to verify the scalability. Silver plated, nickel 200 screens were used for the catalyst bed. Over 250 tests were performed before the final selection of the catalyst bed configuration.

The catalyst bed design variables include bed loading, screen material, screen loading configuration, screen plating processes, screen mesh and wire size, catalyst bed head load uniformity, operational characteristics, and the cost of catalyst bed. Most of these variables have been tested and reported in the literature.[5] For example, McCormick et al.[6] described silver screen catalyst, coated with samarium oxide, for the decomposition of 90-98% H_2O_2. Garwig[7] reported that pure silver metal was found to be more reactive with hydrogen peroxide than silver metal which had been either tarnished or treated with $Sm(NO_3)_3$. The $Sm(NO_3)_3$ treated silver plated screens afforded a "catalyst" which was not reproducible in activity towards H_2O_2. The results of our present tests, with 85% H_2O_2 agree with Garwig's findings. In order to maintain high decomposition efficiency, the silver screens were not samarium oxide coated in the present catalyst bed development program.

The plating process developed for the catalyst bed screens was systematically evaluated using an activity test to determine the optimal plating procedure and silver plating thickness. A one inch diameter catalyst screen was resistance spot welded to a -K type thermocouple and placed into a beaker containing a known volume of hydrogen peroxide. A Keithley TDA8 data acquisition module plugged directly into a PC parallel port, was used to acquire data. Data of the elapsed time for the catalyst to reach maximum temperature and the maximum steam temperature were recorded. Catalyst screens were then punched using a steel rule die and packed into the catalyst bed cartridge. The bed is a modular cartridge design to allow rapid hardware exchange. Distribution and support plates, and anti-channel baffles were used to provide a uniform H_2O_2 flow into the bed preventing H_2O_2 channeling along cartridge wall. Various compression loads were used to pack screens into the cartridge. It was found that the number of screens, the maximum bed loading and the pressure drop across the bed increased with the compression load if the bed depth is kept the same.

The performance of the catalyst bed was determined by measuring the temperature of the decomposed gas and the C* efficiency of the monopropellant engine based on measured chamber pressure (P_c). The C* *efficiency*, η_{C^*}, *and thermal efficiency*, η_T, were calculated as:

$$\eta_{c^*} = \left(P_c A_t / \dot{m}\right) / \left\{ \sqrt{\gamma R T_{dec}} \Big/ \left[\gamma \sqrt{\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}} \right] \right\}$$

$$\eta_T = \left(T_c - T_{amb}\right) / \left(T_{dec} - T_{amb}\right)$$

where A_t, γ, R, T_{dec}, and T_{amb} are throat area, specific heat ratio, gas constant, theoretical decomposition temperature, and ambient peroxide temperature. The R for the decomposed gas for 85% H_2O_2 is 0.091 Btu/lbm/°F and the γ is 1.275. The theoretical decomposition and ambient temperatures were 1173 °F and 67.4 °F, respectively. Measured efficiencies were used to evaluate the performance of the catalyst bed and used as a criterion for the initiation of JP-8 fuel injection during the bipropellant mode testing.

Currently, a catalyst bed configuration has been selected based on bed loading, decomposition performance, and pressure drop. Additionally, the decomposed gas exhibited a high temperature to ensure the auto-ignition of JP-8 fuel. Future efforts on the catalyst bed development will include the evaluation of bed life and the scalability to the catalyst bed design for the 10,000 lbf rocket engine.

<u>Bipropellant Mode Testing</u>

Testing of the 1000-lbf, subscale engine in bipropellant mode is being conducted to gather information required to efficiently the design the 10,000-lbf engine. Issues such as fuel-oxidizer mixing, auto-ignition, injector performance, chamber geometry, wall heat flux, ablative liner char rates, and throat erosion are being investigated through a well-defined test matrix. Results of these investigations are being compiled to optimize features incorporated into the design of the 10,000-lbf engine.

Since no ignition device, such as a spark plug or pyrophoric gas, is used in the proposed engine configuration, auto-ignition is a prerequisite for operation. Auto-ignition is dependent on the temperature of the decomposed oxidizer as well as the fuel residence time within the combustion chamber. The temperature rise associated with the decomposition of 85% hydrogen peroxide is large enough to cause auto-ignition if the fuel residence time is sufficient. This requires a proper chamber geometry to insure that at least a portion of the fuel can mix with the oxidizer and remain in the chamber long enough to vaporize, auto-ignite, and pilot the remaining fuel-oxidizer mixture into full combustion. To better understand these phenomena, tests utilizing various chamber lengths, contraction ratios, combustor velocities, etc., are currently being conducted. Preliminary results show that auto-ignition may be achieved consistently with the proper coupling of combustor geometry and propellant flow conditions.

With the proper selection of chamber geometry, tests are being conducted to screen candidate injector designs. The screening process involves hot-firing the engine in bipropellant mode and measuring the performance of each injector over a range of operating conditions. Primary performance indicators are C* efficiency and thrust efficiency, while wall heat flux and various other parameters serve as secondary indicators. After screening the first series of injector concepts, the concept providing the best overall performance will be selected, optimized, and tested.

Tests will then be conducted with the selected injector concept to investigate the ablation characteristics of a silica-phenolic combustion chamber liner. A test series with varying burn durations has been prescribed. The liner will then be removed and thoroughly examined to determine char rate, char depth, throat erosion, and ablation non-uniformities. The examination is conducted by slicing the liner into thin cross-sections, photographing each section, digitizing each photograph, and analyzing the resulting images through digital image processing techniques. The results of these studies will be used to determine the axial variation of required minimum liner thickness for the 10,000-lbf engine.

Currently, the proper chamber geometry has been selected and tests are being conducted to select a final injector concept. Tests of the ablative liner shall soon be conducted. A photograph of typical test firing is shown in Figure 4.

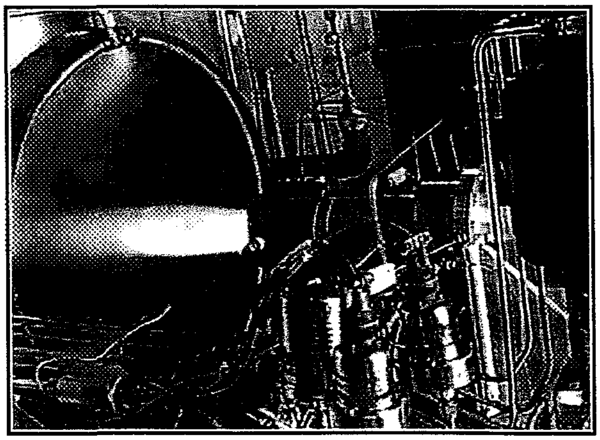

Figure 4. Subscale Testing of USFE using 85% H_2O_2 and JP-8 Fuels

Summary

Hydrogen peroxide offers a number of advantages which clearly indicate that it has a place in the propulsion marketplace. Its nontoxic nature and benign combustion products are a tremendous advantage over many traditional propellants in today's atmosphere of environmental sensitivity. Its storability and high energy density make HTP the ideal choice for certain applications including military systems or volume constrained applications such as the payload bay of an RLV.

The favorable thermo-chemistry of HTP simplifies engine design. The relatively low combustion temperature greatly reduces thermal management issues. Design of bipropellant combustor injectors is simplified due to the ability to employ gas-liquid injection which additionally increases stability margin and results in increased combustion efficiency.

The flexibility of HTP to operate as both an oxidizer and a monopropellant supports a wide range of applications. In a bipropellant capacity the HTP delivers high performance suitable for main engine thrust, vernier, or OMS applications. HTP decomposed through a simple catalyst bed results in good monopropellant performance well suited to ACS/RCS applications. These same peroxide decomposition products can be used to drive turbomachinery for propellant feed, power generation, or hydraulic applications. A combination of these functions results in a simple, low cost, single propellant system well suited for RLV applications.

The Upper Stage Flight Experiment (USFE) focuses on key technologies necessary to demonstrate the ability to fly a low cost system through the use of an inherently simple propulsion system coupled with an innovative, state of the art structure. These technologies, combined with design to cost methodology and the operations cost saving inherent to HTP systems, demonstrate the advantages of this approach over systems employing traditional cryogenic or hypergolic propulsion systems.

Through a series of subscale monopropellant and bipropellant tests, the USFE engine development is gathering the data necessary to complete production of the full-scale engine which is schedule to be ground tested in late 1998.

The key processes necessary to construct the full-scale USFE composite common bulkhead integral structure have been validated through construction of subscale structures which are currently undergoing tests. In addition, the USFE program has generated a significant body of new data related to HTP material compatibility.

References

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