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TRIPROPELLANT COMBUSTION PROCESS

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ABSTRACT

The addition of small amounts of hydrogen to the combustion of LOX/hydrocarbon propellants in large rocket booster engines has the potential to enhance the system stability. This paper describes programs being conducted to evaluate the effects of hydrogen on the combustion of LOX/hydrocarbon propellants at supercritical pressures. Portions of the work described are being accomplished under contract to the Air Force Astronautics Laboratory. In addition, Pratt & Whitney is conducting tripropellant research under internal R&D.

Combustion instability has historically been a problem during the development of large hydrocarbon fueled rocket engines. At the higher combustion chamber pressures expected for the next generation of booster engines, the effect of unstable combustion could be even more destructive. The tripropellant engine cycle takes advantage of the superior cooling characteristics of hydrogen to cool the combustion chamber and a small amount of the hydrogen coolant can be used in the combustion process to enhance the system stability. The benefits foreseen are small propellant droplet size, reduced ignition delay time and increased burning rate, all of which contribute to system stability.

This paper describes three aspects of work that will be accomplished to evaluate tripropellant combustion. The first is laboratory demonstration of the benefits through the evaluation of drop size, ignition delay and burning rate. The second is analytical modeling of the combustion process using the empirical relationship determined in the laboratory. The third is a subscale demonstration in which the system stability will be evaluated. This paper describes the approach for each aspect and presents the analytical models that will be used.

1.0 BACKGROUND

Future space missions will require a family of large launch vehicles powered by new advanced rocket engines. Improvements over current large engines will include higher performance and reduced life cycle cost.

Key elements in achieving high performance are: selection of high energy propellants with an optimum tradeoff between propellant specific impulse and propellant bulk density; and operation at high main chamber combustion pressure. Studies have shown that oxygen burned with a hydrocarbon fuel such as methane, propane, or RP-1 can be used to achieve these requirements.

One chronic development problem with large oxygen/hydrocarbon engines, however, has been combustion instability. Frequently, combustion instability has been encountered, and has been eliminated only after many laborious trial and error modifications. This process is always costly and time consuming and modifications often result in performance losses.

The tripropellant engine cycle provides a means of overcoming some of the costly technical challenges and limitations of oxygen/hydrocarbon bipropellant engines without sacrificing their inherent advantages. It also takes advantage of the favorable cooling characteristics of hydrogen to allow operation at higher combustion chamber pressure than is possible with oxygen/hydrocarbon propellants alone.

For a typical oxygen/hydrocarbon booster engine of 500,000 to 750,000 lb thrust, a hydrogen flowrate equivalent to approximately seven percent of the total fuel flow is required for adequate thrust chamber cooling. Hydrogen flows required to meet the gas generator requirements of the cycle are only 40 to 50 percent of this amount. The logical use for the excess hydrogen is to route it into the main thrust chamber where its addition to the fuel will increase the theoretical specific impulse, and enhance the combustion process. The means of employing the hydrogen to enhance the combustion process, and the extent to which hydrogen provides a benefit, are dependent upon the particular hydrocarbon fuel that is employed.

The technology approach presented herein will provide the initial demonstration of the benefits to be obtained through the addition of hydrogen to the combustion system of an advanced hydrocarbon engine. The approach is structured as follows:

1. Experimental Characterizations — Laboratory testing will be accomplished to provide correlations for propellant drop size, ignition delay and burning rate. The effect of operating conditions and H_2 addition will be determined for CH_4, C_3H_8 and RP-1.

2. Analytical Modeling – Modeling will be accomplished to predict the combustion efficiency and stability of subscale and full scale combustion chamber assemblies. These models will be adjusted as necessary to reflect the data from the above step.

3. Experimental Verification – An experimental certification of the benefits of hydrogen addition to combustion efficiency, burning rate and system stability will be accomplished in test firings of a subscale, 30,000 lb thrust, combustion chamber.

Portions of the work described are being accomplished under contract to the Air Force Astronautics Laboratory. In addition, Pratt & Whitney is conducting tripropellant research under internal R&D.

2.0 EFFECT OF HYDROGEN ADDITION ON COMBUSTION

The effect on performance of adding hydrogen is shown in Table 1.

	Bi-propellants		Tri-propellants		
Fuel	I_{VAC}	Propellant Bulk Density (lb/ft^3)	% H_2**	I_{VAC}	Propellant Bulk Density (lb/ft^3)
CH₄	341.5	49.9	7.7	369.1	44.2
C₃H₆*	333.9	61.8	6.8	363.2	52.2
RP-1	316.0	64.1	9.0	360.1	49.6
H₂	452.8	22.6			

*Subcooled to 155°R
**H₂ shown as a % of total fuel flow
H₂ amount is set by chamber coolant requirement

Table 1. Tripropellant Performance

In addition to the overall performance gain shown, other benefits specific to portions of the combustion process are predicted.

2.1 Propellant Atomization

The addition of hydrogen increases the volume of gaseous fuel which may be used to help atomize liquid propellants. For example, using a coaxial injector with gaseous fuel and liquid oxygen, the gaseous fuel volumetric flow is increased approximately 40 percent by the addition of three percent hydrogen by weight. Fuel injection velocity is also increased. Based upon the correlation of Lefebvre, reference 1, up to a 17 percent reduction in Sauter mean diameter would result. However, the Lefebvre correlation is based on data taken at very different gas and liquid properties than those corresponding to high pressure rocket conditions. Experimental confirmation at more representative conditions will be accomplished as described later in

this paper. The atomization characteristics of two basic types of injection elements will be determined as functions of fluid properties, geometry and operating conditions. The injection element types to be characterized are the nonimpingement and the impingement types. These types represent basically different atomization mechanisms and should allow some application of the characterization of the atomization to other configurations which employ the same atomization mechanism, (i.e., swirl coaxial to shear coaxial and like doublet to unlike doublet).

2.2   Combustion Efficiency

Laboratory combustion experiments with hydrogen/hydrocarbon mixtures have verified that the addition of hydrogen reduces ignition delays, increases droplet burning rate and flame speed, and broadens flammability limits, references 2 through 6. These factors should contribute to increased combustion efficiency; however, the available data pertaining to the effect of hydrogen addition on ignition delay and burning rate are somewhat conflicting, and have been measured at conditions which are not representative of the condition existing in a high pressure rocket. The experimentation described later in this paper will provide data which can be used for advanced high pressure rocket engines.

3.0   TECHNICAL APPROACH

3.1   Analytical Modeling

Most commonly used models of steady-state rocket combustion are based upon the assumption that droplet vaporization is the controlling mechanism in establishing combustion residence time. While these models have proven highly useful in combustion at moderate chamber pressure (100 to 1000 psi), the models break down at the current conditions of interest. There are two reasons why a different approach to the combustion modeling is now required.

First, when a droplet is heated above its critical temperature and the total pressure of the environment is above the droplet critical pressure, boiling cannot occur. Under these conditions the small pockets of propellant, which technically are no longer droplets, must be dispersed through diffusion or forced convection. Both the rate of dispersion and the rate-of-change of dispersion as functions of temperature and pressure are different than for subcritical vaporization.

Second, the implied assumption in using droplet vaporization as the controlling combustion mechanism is the chemical reaction time can be neglected. This assumption has been justified by citing the very high reaction rates at equilibrium rocket combustion temperatures. In practice, however, there is a chemical delay time or ignition delay which is the time between when the reactants first reach their spontaneous ignition temperature and the time they actually begin to burn. The effective temperature for this process is somewhat above the reactant spontaneous ignition temperature, but well below the equilibrium combustion temperature. In a highly atomized gas-liquid

system the relative importance of ignition delay increases. At conditions expected for a a full scale LOX/hydrocarbon engine ignition delay is predicted to be an important factor in determination of combustion efficiency and even more critical with regard to combustion stability.

Pratt & Whitney has developed a rocket combustion model which is directly aimed at the high pressure conditions planned for the STBE. The elements of the model are drop formation, drop heating, ignition delay, and burning. The experimentation described later will provide the quantitative data necessary to more accurately model the oxygen-hydrocarbon high pressure combustion process and will also establish the incremental benefit of hydrogen addition to each of these processes.

3.1.1 Drop Formation

The first step in the high pressure combustion model is determination of the injected drop size and drop size distribution. Most of the past and ongoing combustion studies have utilized empirically derived correlations of spray characteristics such as those given in References 1 and 7. Unfortunately, existing correlations are based on conditions far different than those required for an advanced LOX/hydrocarbon engine and considerable extrapolation is involved.

The injector spray modeling at the United Technologies Research Center (UTRC) supports this analytical modeling. These data will be used to generate a correlation which relates liquid droplet size and distribution to injector geometry and operating conditions. With the proper selection of test fluids, it is possible to provide a correlation for droplet size and number which requires only modest extrapolation to actual hot fire conditions, as opposed to current correlations which often require extrapolation by more than a factor of ten.

3.1.2 Drop Heating

Using the predicted droplet size and distribution, droplet heating is calculated using methods described by Wieber (Reference 8). The calculation is used to determine the time required to heat the droplet to its boiling point or critical temperature and establishes how much of the propellant vaporizes prior to reaching its critical temperature and how much must diffuse under supercritical conditions.

Reference 8 gives the calculated droplet heating characteristics for two representative propellants, liquid oxygen and heptane, at combustion pressures above the liquid critical pressure. At chamber pressures of 1500 psia or less, with heptane, (typical of a liquid hydrocarbon fuel), a significant portion of the life of a heptane droplet is spent in a vaporization mode with vaporization controlling the combustion rate. In the case of the liquid oxygen droplet, there is very little vaporization before the drop reaches critical temperature. This difference is of particular importance to combustion stability.

According to the Rayleigh stability criteria, if energy is added to an instability while the pressure is increasing, the system can become unstable. The vaporization rate of a droplet is increased by increasing pressure which results in an increase in combustion energy with increasing pressure. This effect satisfies the Rayleigh criterion for instability. The oxygen dispersion is controlled by diffusion after the drop reaches critical temperature. Reference 9 shows that increasing pressure will reduce the diffusion controlled combustion rate, and energy will be added 90 degrees out of phase with the pressure waves, a trend which is clearly stabilizing.

3.1.3 Ignition Delay

Once the droplet is heated to its spontaneous ignition temperature, the ignition delay establishes the additional shift of the flame front downstream of the injection plane. While the ignition delay time is believed to be of increasing importance at high pressure the available data are inadequate for extrapolation to the condition of interest. Testing will be conducted at UTRC under this program to define ignition delay characteristics of methane, propane and RP-1 with and without hydrogen addition. The testing and the form of the correlation to predict ignition delay times are presented later in this paper.

3.1.4 Burning Rate

The reactant burnrate is used to determine the required burning length downstream of the flamefront. The flamefront is located from the experimentally determined ignition delay time, droplet formation plane and droplet heating time. Since a gaseous fuel jet is expanding once it leaves the injector, the velocity must be integrated over a series of axial increments until the travel time of the jet equals the ignition delay time, thus providing the distance the fuel jet and accompanying droplets have traveled before combustion begins (Reference 10).

The calculation of combustion burning rate is based on the model given in Reference 9. In this model, the combustion rate is controlled by diffusion once the liquid droplet reaches critical conditions, i.e., when the droplet reaches its critical temperature and the combustion process is above the critical pressure of the fluid. Under these conditions, increasing the pressure increases the density of the diffusion reactants which slows down the rate of diffusion and concomitantly reduces the combustion rate. The experimental verification of this model is given in Reference 11.

3.1.5 Combustion Stability

High frequency combustion instability, or acoustic instability, is the most destructive instability, and is generally the predominant instability in a high efficiency, high energy release combustion system. Several analytical models are available which allow an evaluation of the combustion system acoustic stability

characteristics. They are:

o   The Crocco-Cheng Sensitive Time Lag Theory
o   The Priem-Guentert Analysis
o   The Heidmann-Feiler Analysis
o   The Dykema Analysis
o   The Leeper Modal Energy Analysis

P&W prefers the Sensitive Time Lag Theory of Crocco and Cheng, (Reference 12). This analysis allows the characterization of the effect of hydrogen addition on combustion stability, it is complete in the sense that all significant contributions to combustion stability characteristics are included, it allows characterization of the effect of an acoustic liner, it is capable of characterizing longitudinal, tangential and radial modes, and there is a fairly extensive data base of numerical predictions and comparisons with experimental data in the literature.

A typical computer code, similar to the one that P&W uses is given in References 13 and 14. A simplified version of this computer code, which will characterize the combustion stability of a system employing an acoustic liner, is given in Reference 15. Empirical values of the combustion response parameters, (sensitive time lag and pressure interaction index), are presented in References 14,16,17 and 18.

Most of the experimental data available are for oxygen/hydrogen combustion systems, with very little data available for oxygen/hydrocarbon combustion response parameters and even less on the effect of hydrogen addition to an oxygen/hydrocarbon system. These data will be generated through experimental programs, and will allow the sensitive time lag analysis to be modified to reflect the effect of hydrogen addition on the combustion stability characteristics of oxygen/methane, oxygen/propane and oxygen/RP-1 high pressure combustion systems. Specifically, the experimental data generated for these combustion systems will provide burning rates and ignition delays as functions of hydrogen concentration. These data will be used directly to modify the sensitive time lag analytical code. The burning rate data will be used directly to modify the sensitive time lag. The ignition delay represents the time lag required for preparation of the reactants prior to combustion. The time lag creates a stored volume of unreacted propellant between the injector and the flamefront. The stored volume is an energy reservoir which can respond to combustion pressure perturbations; increasing the ignition delay increases the mass of unreacted propellants, and therefore, the strength of the combustion response. The experimental data generated for oxygen/methane, oxygen/propane and oxygen/RP-1 combustion systems with hydrogen addition will be used to modify the pressure interaction index in the sensitive time lag analysis.

3.1.6   Model Application

The models described in the foregoing discussion are the primary tools P&W uses in defining the geometry and flow requirements of

injectors and thrust chambers. These tools will be updated as experimental data becomes available. The most important data sources for the model enhancement and anchoring are:

1.   The drop size measurements which will provide the starting point for calculation of combustion efficiency in the performance model.

2.   The ignition delay tests which provides basic data for both the performance and stability models.

3.   The burning rate experiments which provide a basis for anchoring the performance and stability models.

3.2   Laboratory Characterizations

The objective of these experiments is to develop correlations for drop size characteristics, ignition delay and burning rate for the three candidate hydrocarbon fuels. This experimentation will be conducted at United Technologies Research Center (UTRC) in East Hartford, CT.

3.2.1   Injected Liquid Size and Distribution

The objective of this experiment is to develop correlations which relate droplet size and distribution to injector geometry and operating conditions. These correlations require information regarding injector geometry, propellant densities, surface tension, relative velocities, and liquid viscosity. Tests will be performed in which these parameters are varied over a range sufficient to enable a prediction of droplet size at the design operating condition of a subscale and full scale combustion chamber.

The test apparatus selected for use in this program is shown in Figure 1.
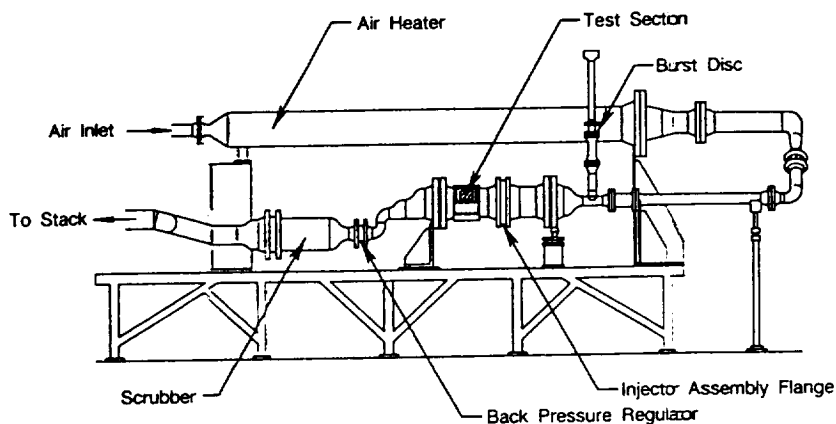
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Figure 1. High Pressure Spray Facility

This high pressure spray facility can be operated from atmospheric pressure to 500 psig in the test section. Windows are mounted on the test section and provide optical access to permit use of a Malvern particle size analyzer and an Aerometrics Phase-Doppler analyzer to determine droplet size and size distribution and high speed cinematography to record the early stages of spray development.

Two types of injection elements will be evaluated during this test program. Coaxial elements will be tested in both the liquid/gas and liquid/liquid configurations and impinging like-on-like doublet and pentad configurations will be tested for liquid-liquid application.

For the coaxial configurations shown in Figure 2. The oxidizer enters through tangential slots into a central tube and fuel is injected coaxially to it with liquid/gas (i.e., CH4, C3H8) the hydrogen is premixed with the fuel and is also used as a transpiration coolant for the faceplate. For the liquid/liquid configuration, the hydrogen is added to the combustion process only through the faceplate.
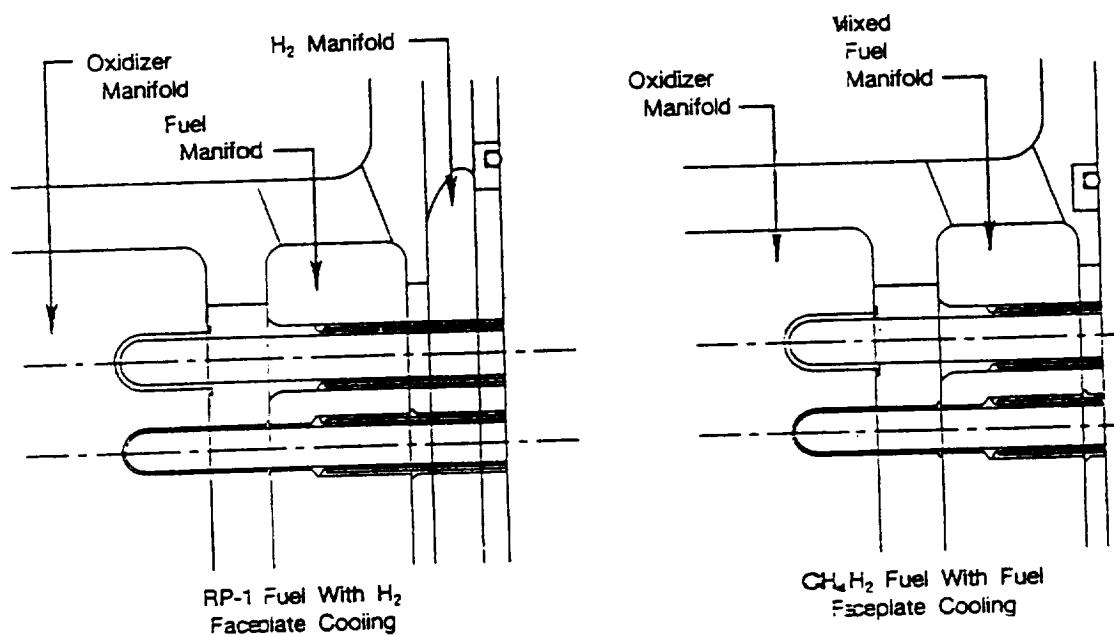

Figure 2. Coaxial Injector Configurations

The impinging injector flows are shown in Figure 3. For the like-on-like configuration, two oxidizer streams impinge on each other and two fuel streams impinge on each other and the resultant spread of droplets then intermix; the hydrogen is added through the faceplate. In the pentad configuration, the oxidizer, fuel and hydrogen impinge at a common point.
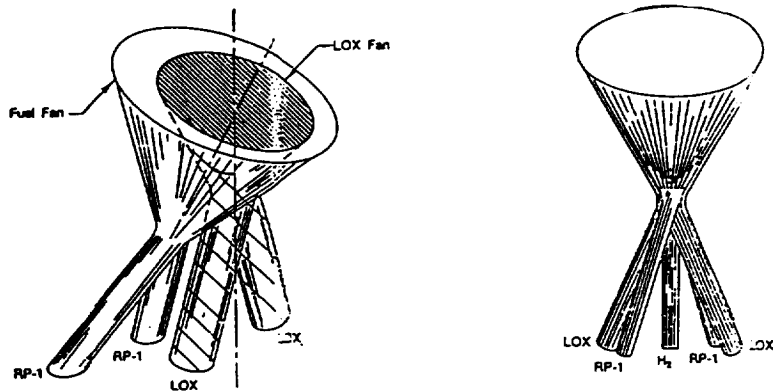
Figure 3.   Impinging Injector Flows

Water, Freon 113 and Jet-A   shall be used as simulants   for the liquid propellants.   Table 2 presents a comparison of the values   of the important properties of the actual liquids with those of the simulants.   It can be seen that, in principle, the range of each parameter can be covered.

	Actual Propellants		Simulants		
	Oxygen	RP1	H_2O	Freon 113	Jet-A
Temperature (°F)	-270	77	77	77	77
Surface Tension (kg/s^2)	0.00955	0.0217	0.0725	0.0173	0.0259
Density (lbm/ft^3)	70.2	47.5	62.2	97.7	49.9
Viscosity	0.00013	0.001648	0.00086	0.00068	0.00153

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Table 2.   Drop Size Simulants

Even though the   surface tension and   viscosity of LOX   are factors of 2.0 and 5.0 respectively, lower than the Freon 113   simulant, these fluid properties usually have exponents of 0.25 to 0.45 in most spray correlation equations.   Said exponents   reduce the   extrapolation from factors of 2.0 and 5.0 to factors of 1.2 (to 1.4) and 1.5 (to 2.1).

The droplet size distribution data will be represented by a Rosin-Rammler distribution.   The following equation describes this distribution:

$$R = \exp(-((d/X)n))$$

where

d = Droplet size

R = Cumulative volume fraction of droplets
    larger than size d

X, n = Size parameter   and width of the   distribution, respectively

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X and n will be determined from the measurements and correlated to the following parameters: fuel to oxidizer momentum ratio, relative velocity between gas and liquid flows, injector exit gas density, liquid properties, configuration, injector liquid pressure drop, spray angle.

Correlations of the following form will then be developed:

$$Y = C1(P1c2P2c3 \ldots Pnc(n + 1))$$

where

$$C1, C2, \ldots, \text{ and } C(n+1) = \text{Empirical constants}$$
$$P1, P2, \ldots, \text{ and } Pn = \text{Injector operating variables}$$

A linear regression program will be used to determine C1, C2, ..., and C(n+1). The result will be correlations that relate the droplet size distribution parameters to the injector operating parameters.

3.2.2   Experimental Characterization of Ignition Delay

Ignition delay correlations will be developed in a form that is suitable for application to the design of tripropellant combustors. Three fuels (methane, RP-1 and propane) will be tested both with and without small additions of hydrogen to determine the effect of the addition at the anticipated engine design points and beyond.

The test apparatus (shown in figure 4) used in previous autoignition testing at UTRC will be used in this program.
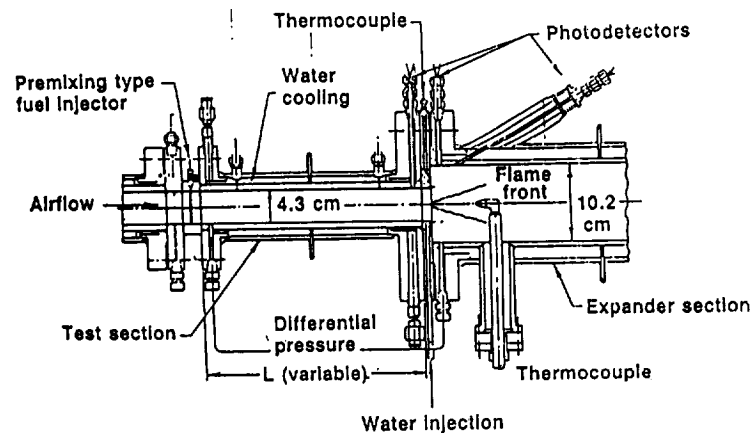

Figure 4. Autoignition Test Apparatus

A special premixing-type fuel injector, developed and used extensively at UTRC, will be used during these experiments. The use of this injector will ensure the generation of a uniform fuel-air distribution in the shortest distance (time) possible and with a minimum flow disturbance. Extensive qualification tests (Refs. 19 and 20) have

demonstrated that this design is capable of producing the required mixture uniformity using either gaseous or liquid fuels. For tests with liquid fuels, a separate multiple-source injector will be used for hydrogen addition.

The normal operating procedure for acquiring ignition delay data consists of establishing a prescribed condition, e.g., pressure, composition, and flow rate, within the test duct and gradually increasing the inlet air temperature until autoignition occurs at the autoignition station located at the exit of the test section. The occurrence of autoignition is determined by: 1) a thermocouple probe located in the expander section and 2) a differential pressure transducer monitoring the pressure rise across the flame front. Photodectors are also available to detect ignition.

This test arrangement permits independent variation of each of the important variables, i.e., pressure, temperature, velocity, residence time, and composition, within a fixed range of test conditions. The ignition delay time is equated to the residence time of the mixture between the point of fuel injection and the location of the water quench immediately upstream of the expander section. The residence time is computed based upon the average flow velocity as calculated from the inlet temperature, pressure, and mass flow rates.

Variations in the ignition delay time will be developed by varying the test section length. As a consequence of the length changes, the air temperature required for ignition will change from test to test, ultimately establishing the required interrelationship between pressure, temperature, composition, and ignition delay time.

The ignition delay time (t) will be calculated using the relationship

$$\tau = \frac{L}{u} \tag{1}$$

where L is the length of the test section and u is the mean freestream flow velocity. The test-section length is defined as the distance between the injector and the test-section exit. The test-section length, the mixture composition, and the mixture temperature comprise the independent variables which result in ignition delay time variations at a constant value of test-section pressure.

In general, ignition delay times (t) are correlated with oxygen concentration, fuel concentration, and temperature according to the following expression:

$$\tau = A \exp(E/RT) [O_2]^y [Fuel]^z, \tag{2}$$

where E is the global activation energy corresponding to the physical and chemical processes that occur during the induction period, R is the universal gas constant, and A, m, and n are empirical constants. The

concentration terms are calculated from the equation:

$$\{\ \}_i = \frac{X_i P}{RT},\qquad (3)$$

where xi is the mole fraction of the i-th species. For this investigation, ignition delay time will be correlated with the test section temperature and mixture composition using Eq.2. Using this correlation, the data required will be presented as a function of reciprocal temperature, 1/T, where T is the calculated mixture temperature.

3.2.3 Experimental Characterization of Burning Rate

The objective of the burning rate investigations is to determine the influence of hydrogen addition on combustion characteristics. In addition, burning rate measurements will reflect the degree of vaporization and mixing achieved by different injector configurations. The investigations will be conducted with the three candidate fuels using a subscale-diameter thrust chamber with a reduced number of full-size injector elements of the configurations described earlier. The completeness of combustion will be assessed by means of conventional rocket engine performance parameters, e.g., c* efficiency as well as by using advanced laser diagnostics at the exit of the test chambers to make accurate, in situ measurements of gas temperature and chemical species concentrations.

The combustion chamber will have an inside diameter of approximately 2 inches, and will be fabricated in lengths of 8,10 and 14 inches. Each chamber length will be water-cooled having an inner wall made of copper and will have a throat diameter of approximately 1.1 inches at the exit plane (contraction ratio 3). This test apparatus is shown schematically in Figure 5.
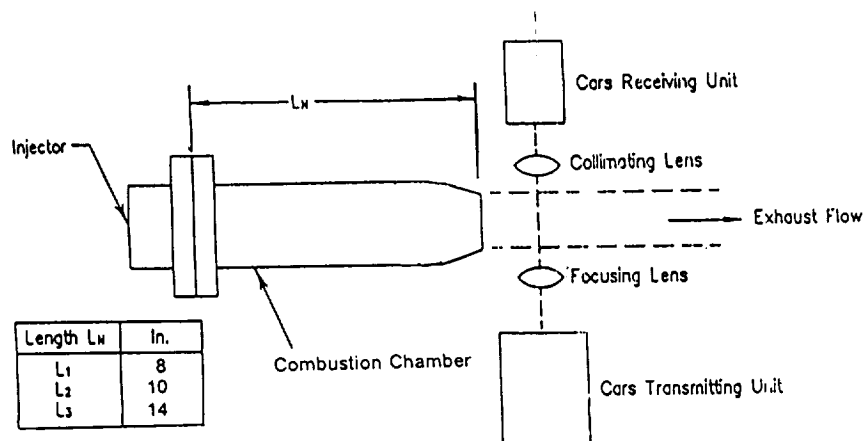

Figure 5. Burning Rate Test Apparatus

All tests will be conducted at the engine design condition mixture ratio and at a chamber pressure of approximately 1500 psia. The combustion chamber lengths will be selected based upon evaluations of combustion performance obtained from the combustion models.

Exhaust gas temperature and species concentration data will be obtained using advanced laser diagnostic techniques available at UTRC. The most appropriate technique for the proposed investigations is coherent anti-stokes Raman spectroscopy, (CARS), which is a wave-mixing technique wherein laser beams at two frequencies are mixed to produce a coherent signal beam at a third frequency. Adjustment of the resultant frequency to Raman-active vibrational-rotational modes of the constituent molecules permits individual species to be measured. Thermometry is derived from beam signature analysis, whereas species concentrations are determined from the strength of the CARS signals.

Combustion performance will be evaluated by comparing measured values of characteristic velocity with theoretical values obtained, assuming frozen flow of the combustion gases through the nozzle. In addition, key exhaust species concentrations such as H_2O, CO, CO_2, and unburned fuel obtained from CARS measurements will be compared with species concentrations predicted by chemical equilibrium calculations to indicate the degree of completeness of combustion achieved in the experimental thrust chamber firings. Correlations of c* efficiencies and species concentrations as functions of chamber length, or L*, and amount of hydrogen addition will be developed.

3.3   Experimental Verification

The final phase of this technology investigation will be the anchoring of the analytical codes developed earlier. Using a subscale combustion chamber which will be tested at the Air Force Astronautics Laboratory. The fuel and the injector configuration to be used for this testing will be based on the results of the laboratory testing and the predictions from the analytical models. The combination which shows the greatest gains in performance and stability margin will be selected.

The baseline combustor length was selected to provide combustion efficiencies which are reduced enough without hydrogen to allow differences in performance can be observed when the hydrogen is added. In addition, the test article will be configured to allow for an increase in the combustor length to permit positive determination of the benefits of hydrogen addition to the combustion process. This will be accomplished using a spool piece which can be added to the combustor to increase the overall length. The predicted effects of the length and hydrogen addition are shown in Figure 6.

The chamber and spool piece will be constructed similar to that used for the experimental work at UTRC and will be water cooled. The contraction ratio has been set at 2.92 to be similar to the combustor used for testing natural gas under a NASA program. This was done to allow direct comparison to that data for the effects of hydrogen addition.
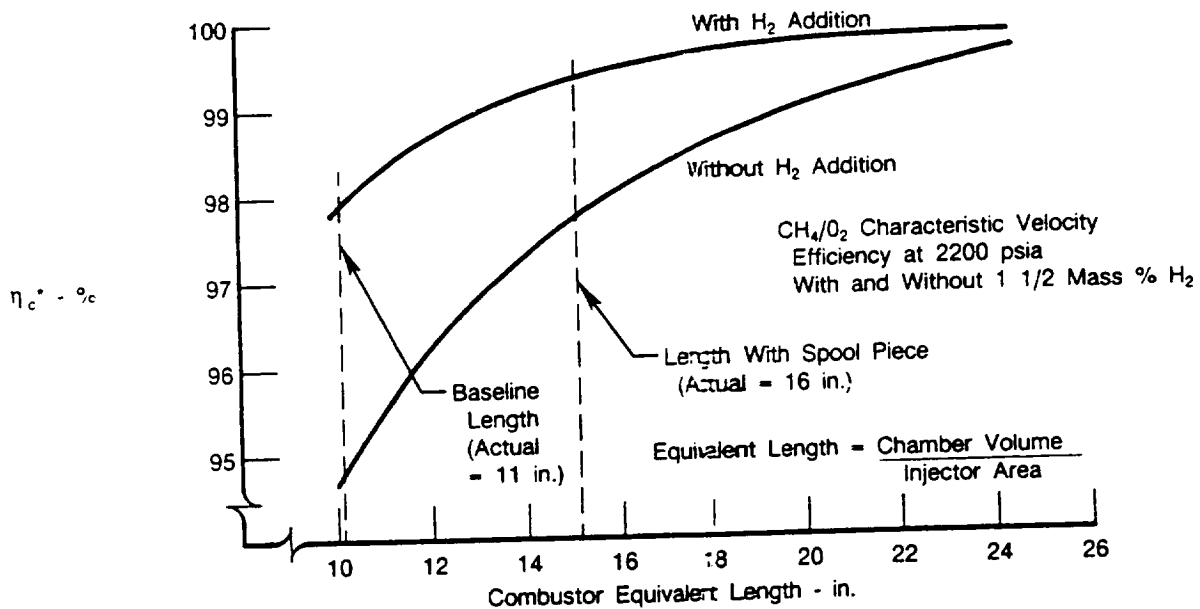
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Figure 6. Verification Test Configurations

The test objectives are as follows:

o   Clearly demonstrate the enhancement of the combustion process through hydrogen addition

o   Provide data for possible further improvements in the burning rate of the models

o   Demonstrate tripropellant combustion stability when subjected to an overpressure disturbance

o   Verify the validity of the combustion and stability models

The first objective will be achieved by conducting back-to-back tests with and without hydrogen added. The second objective will be achieved by installing the spool piece and determining the change in the combustion efficiency. The third objective will be achieved by activating a bomb in the combustion chamber during the firing and determining the system damping capability. All data generated during the test program will be analyzed and compared to the predictions made with the models to achieve the fourth objective.

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4.0 CONCLUSIONS

The program described in this paper provides an approach to determine the benefits of hydrogen addition to the combustion of hydrocarbon propellants. The basic elements of the combustion process will be examined at the laboratory level to provide correlations which can be applied to rocket engine designs. Analytical models for combustion will be modified based on the results of that testing. Verification of the model predictions will be conducted at the subscale level. This approach will result in verified correlations which can be used for design of a full scale tripropellant rocket engine.

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