60° the efficiency is reduced to $\epsilon = 1.05$ with a corresponding weight increase of 2.0% over the optimum.

By combining Eqs. (A9) and (A10) the corrugation radius index, for $K = 8.0$ can be expressed as follows:

$$(2R/d) = 1.34[\sin\phi/(\phi\epsilon^{1/2})]^{5/3}\eta_T^{1/3}\eta_w^{-5/6}(N_{xy}/Ed)^{1/6} \quad \text{(A12)}$$

The skin thickness can be obtained from Eq. (A6).

Optimum angle under minimum gage constraint

It was previously shown that efficiency can be maximized independently of load intensity. This is only true, however, if the skin gage is an open variable, ie., free to assume any positive real number. If it is assumed that t is constrained at t_m, Eq. (A10) becomes

$$(N_{xy})/(\eta_w Ed) = [1.088K^{1/2}\{f(\phi)\}^{1/2}](t_m/d)^2 \quad \text{(A13)}$$

and, consequently

$$\{f(\phi)\}^{1/2} = 0.92\{[N_{xy}/(\eta_w Ed)]/[K^{1/2}(t_m/d)^2]\} \quad \text{(A14)}$$

is load dependent if the efficiency equation is still to be satisfied. Equation (A14) can be evaluated graphically as a function of load index with t_m/d as a parameter. Figure 6 shows a typical parametric curve with percentage weight savings indicated over the 80° configuration with t constrained at t_m.

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MARCH-APRIL J. AIRCRAFT VOL. 3, NO. 2

An Investigation of Catalytic Ignition of JP-5 and Air Mixtures

STEPHEN E. GRENLESKI* AND FELIX FALK†
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Md.

An experimental investigation of the ignition of JP-5 and air mixtures by platinum catalysts was made using sectional and large-scale ramjet engine baffle combustors. Ignition delay data are presented for combustion chamber static pressures of 0.5 to 9.0 atm, inlet air total temperatures of 580° to 1280°F, and fuel-air ratios of 0.007 to 0.09. A thermal model is used to explain the igniter operation.

Introduction

Ignition of the fuel-air mixtures at various pressures and temperatures is one of many problem areas encountered in ramjet combustor development. Experiments conducted by the General Electric Company,[1] in which platinum was used as an igniter in the afterburner of gas turbine engines, aroused interest in the application of platinum igniters to ramjet engines.

The purpose of this paper is to present the results of an investigation which applies the catalysis of JP-5 and air mixtures by platinum (for ignition and oxidation) to ramjet engine baffle combustors and test conditions.

Received May 27, 1965; revision received November 15, 1965. This work was supported by the U. S. Bureau of Naval Weapons under Contract NOw 62-0604-c. The authors wish to acknowledge the encouragement of W. B. Shippen of the Applied Physics Laboratory (APL) and the assistance of J. Funk and E. Taylor (APL) and J. Tucker of the Ordnance Aerophysics Laboratory (OAL) during this program.

* Engineer, Hypersonic Propulsion Group.
† Chemist, Propulsion Engineering Group. Member AIAA.

Experimental Results

This investigation of catalytic ignition of JP-5 and air mixtures was carried out in two distinct phases: first as sectional

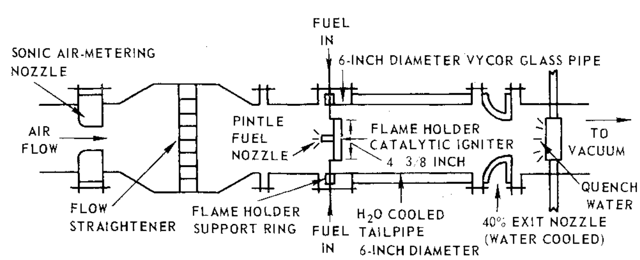


Fig. 1 Schematic sketch of catalytic igniter sectional test setup.

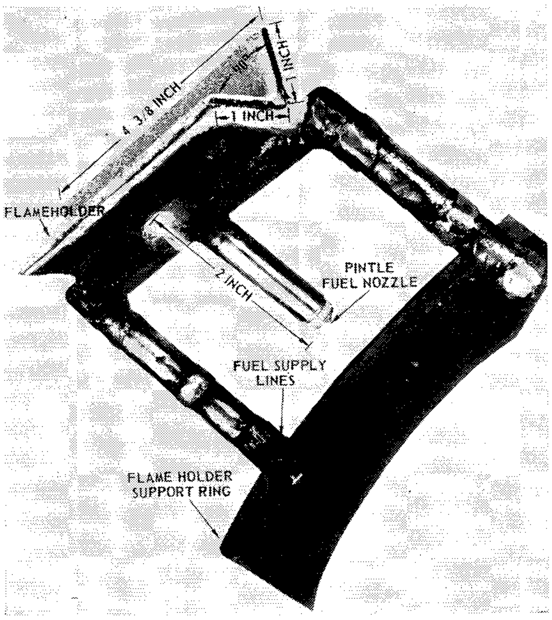


Fig. 2 Typical flameholder-fuel injector assembly.

tests and then with large-scale ramjet engine baffle combustor tests. Sectional tests were conducted to demonstrate the applicability of the concept and to indicate the relative merits of the various igniter configurations proposed. Large-scale combustor tests were then made to determine the operating characteristics of the igniter selected from the sectional tests in an actual engine environment.

Sectional Test Results

Tests were carried out at the APL facility, which was capable of providing $1\frac{1}{2}$ lb/sec of air at total temperatures up to 1400°F to the setup shown in Fig. 1. The angle-iron flameholder was placed across the duct with its axis on a diameter of the tailpipe as shown in Fig. 2. In most of the tests, the lee side of the gutter was enclosed to permit fuel cooling of the flameholder. Unheated (approximately 70°F) fuel, JP-5, was injected contrastream through a variable area pintle nozzle mounted on the centerline of the duct. Instrumentation was provided to determine air flow rate, air total temperature at the combustion chamber inlet, fuel flow rate, combustion chamber static pressure, and ignition delay.

Preliminary tests were carried out with igniters provided by the General Electric Company. These igniter designs consisted of porous firebrick disks flame-sprayed with platinum,

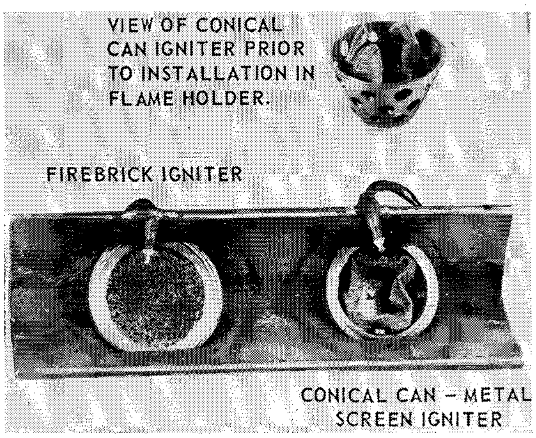


Fig. 3 View of firebrick (sprayed with platinum) igniter and platinum-rhodium metal screen igniter inside a perforated conical can looking upstream.

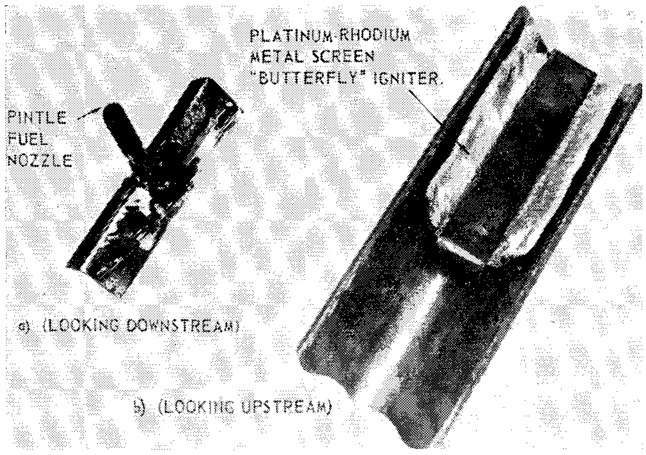


Fig. 4 Two views of uncooled flameholder with "butterfly" igniter attached.

platinum metal screen mounted in a conical can, and rectangular layers of platinum metal screen which could be simply attached to the lee side of the flameholder. Figure 3 presents a view, looking upstream, showing both a firebrick igniter and a can igniter installed in a combustor. Data on ignition delay (measured from the initial fuel pressure rise at the combustor to initial combustion chamber static pressure rise) for these igniters are listed in Table 1. Movies indicated that the fuel-air mixture was ignited most rapidly by the firebrick igniter. Indication of ignition by temperature rise, using the thermocouples shown attached to the flameholder, was not better than ignition indication by pressure rise. Therefore, to simplify the test setup, the thermocouples were not used in subsequent runs.

Figure 4 shows views, looking both upstream and downstream, of a gutter with a rectangular "butterfly" igniter, $1\frac{1}{8} \times 2$ in. attached to the aft surface. This igniter was made of 21 layers of commercially available 0.003-in.-diam, 80-mesh, 90% type A Pt-10% Rh metal screen. With this configuration, ignition was obtained down to an air temperature of 700°F for $0.034 < \text{fuel/air} < 0.068$. Movies showed the unsupported igniter screen on both sides of the attachment band moving about in the recirculation zone by the action of the turbulent gas flow. For the igniter burning time of 3.2 min there was no evidence that the repeated flexing was causing fatigue failure of the wires, and therefore it was not a durability problem. From these preliminary tests with the igniter configurations described, it was concluded that the butterfly igniter is an extremely practical design for use with baffle combustors, and one that warranted further work.

A fuel-cooled gutter combustor was constructed and the butterfly igniter was attached to the downstream surface. Figure 5 shows ignition delay as a function of fuel-air ratio for inlet air temperatures of 900°, 1095°, and 1280°F with this configuration. One notes that as the inlet air temperature is increased the ignition delay time is decreased and the fuel-air range for successful ignition is increased.

To investigate the effect of flameholder insulation on catalytic ignition characteristics, the aft surface of the fuel-

Table 1 Ignition delays for p_{cc} = 0.5 atm

Run no.	T_{air}, °F	W_a, lb/sec	W_f/W_a	Ignition delay, sec
1	1290	1.54	0.021	3.0
2	1290	1.55	0.032	2.0
3	1290	1.54	0.007	3.3
4	700	1.57	0.013	>30
5	700	1.56	0.032	>30
6	700	1.57	0.061	>30
7	1280	1.44	0.033	4.9
8	1280	1.52	0.034	4.1

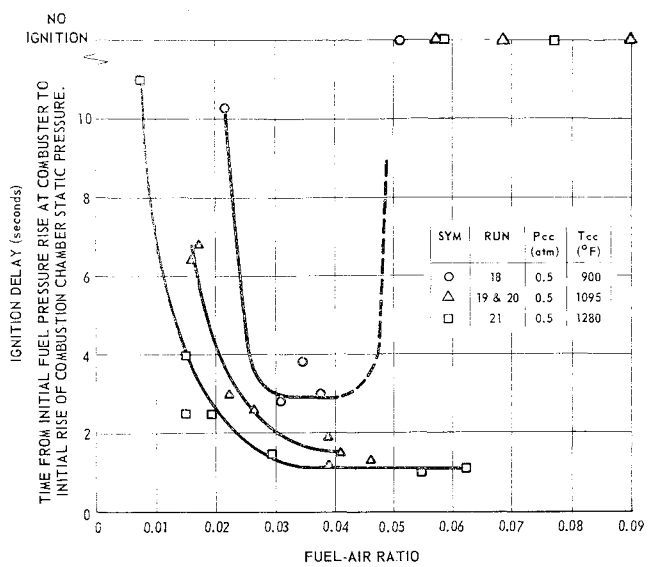


Fig. 5 Ignition delay vs combustor fuel-air ratio at constant combustion chamber static pressure; uninsulated sectional fuel cooled combustor; 21-layer 90% Pt-10% Rh metal screen igniter; JP-5 fuel.

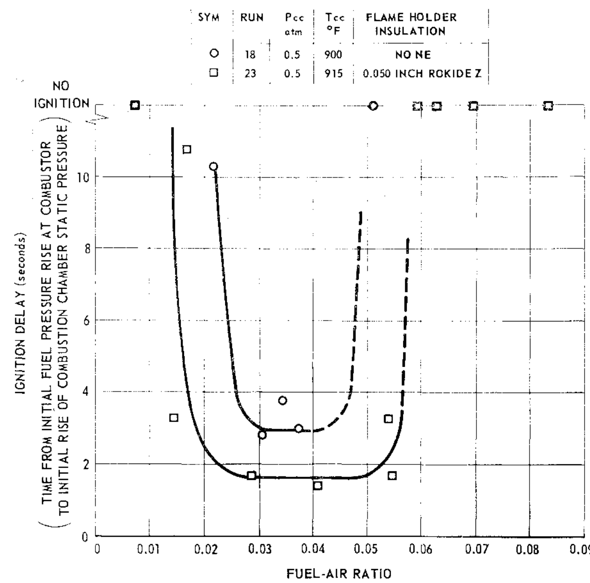


Fig. 7 Ignition delay vs combustor fuel-air ratio at constant combustion chamber static pressure and constant combustion chamber air total temperature; sectional fuel cooled combustor; 21-layer 90% Pt-10% Rh metal screen igniter; JP-5 fuel.

cooled gutter was flame-sprayed with Rokide Z (zirconium oxide) to a thickness of 0.050 in. (Fig. 6). The ignition data plotted in Fig. 7 demonstrate that the addition of Rokide significantly extends the ignition range of this configuration. Also, one notes that for a given fuel-air ratio, the ignition delay time is decreased by the addition of the insulation.

To determine the effect of igniter wire size upon durability, a combination igniter, which had 0.003-in.-diam wire screen inside of a single fold of 0.008-in.-diam wire screen did not improve durability, but it did have the adverse effect of increasing ignition delay and narrowing the ignition limits.

For the sake of completeness, it should be mentioned that a 0.004-in. layer of platinum, flame-sprayed on the Rokide Z (surface visible in Fig. 2), was investigated as a possible substitute for the wire screen. Although hydrogen-air mixtures have been burned successfully on platinum-coated alumina at surface temperatures as low as 600°F,[2] this platinum-coated Rokide Z failed to provide ignition even at air temperatures as high as 1400°F.

Large-Scale Test Results

Large-scale tests were conducted using the combustor shown in Fig. 8. The aft surfaces of the two concentric fuel-cooled gutters, approximately 8 and 14 in. in diameter, are coated with flame-sprayed zirconium oxide. Contrastream conical spray fuel injectors were mounted to, and upstream of, each flameholder in an arrangement similar to that already described for the sectional models. The combustion chamber was 16 in. in diameter and was followed by a 40% sonic exit nozzle. These tests were conducted at the OAL, Daingerfield, Texas.

The objectives of the large-scale tests were to determine: 1) the optimum location for the catalyst, 2) the effect of combustion chamber pressure on ignition delay, 3) the optimum amount of igniter metal screen, and 4) the effect of air temperature on ignition delay.

To determine the optimum location for the catalyst, the "shotgun" approach was used. Four igniters (21 layers of 0.003-in.-diam metal screen) were attached in various positions on the outer gutter, thought to represent different local fuel-air ratio regions, and a run was made with all igniters in place. The four igniter positions were: next to the electrical igniter shroud, midway between two fuel injectors, centered directly behind one fuel injector, and centered directly behind a combustor strut. Movie camera observations (viewing up the tailpipe) of the igniters in operation indicated that the igniter downstream of the strut gave the most rapid ignition. All testing was then continued with catalysts in this location.

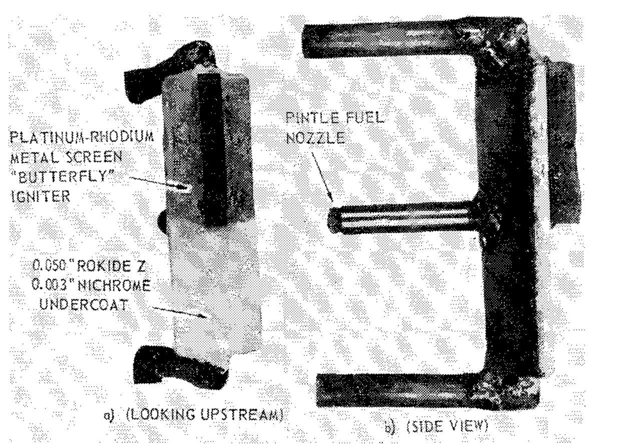


Fig. 6 Two views of fuel cooled gutter, with aft surface coated with Rokide Z, showing "butterfly" igniter attached.

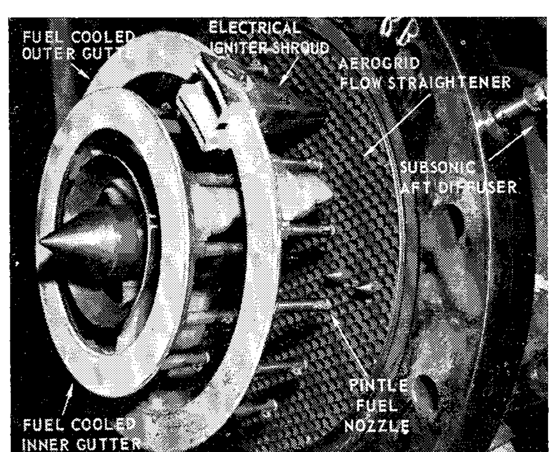


Fig. 8 Large-scale ramjet engine combustor looking upstream.

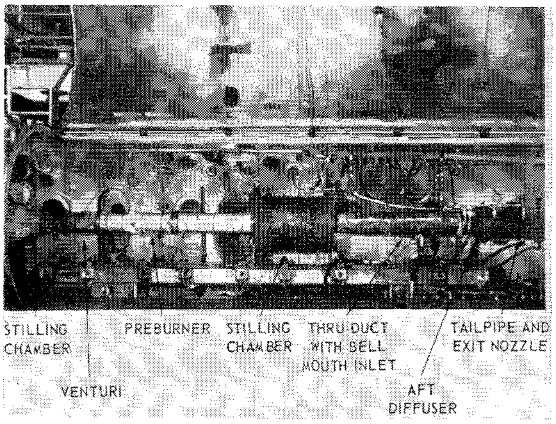


Fig. 9 Large-scale catalytic igniter test setup at OAL, Daingerfield, Texas; air flow from left to right.

To determine the pressure effect, tests were made at combustion chamber pressures of 1, 2, and 5 atm.‡ Clean air temperatures up to 950°F were possible. To test at air temperature above 950°F, clean air at 900°F was vitiated in a JP-5 preburner downstream of the air metering venturi. To test at air pressures above 5 atm vitiation was also required, but from a lower temperature (~100°F). The complete large-scale test setup is shown in Fig. 9.

At 1 atm, ignition did not occur until temperatures in excess of 1200°F were reached even though sectional tests had resulted in ignitions at $\frac{1}{2}$ atm at 900°F. Tests at 2 and 5 atm were more successful, however, with ignition delays§ of less than 1 sec being achieved with air temperatures of approximately 700°F. Figure 10 indicates the typical pressure effect found throughout the entire test program. As the chamber pressure is increased from 2 to 5 atm, the lean ignition limit is decreased from fuel/air $\approx$ 0.047 to fuel/air $\approx$ 0.027, respectively.

Using the butterfly igniter material previously described, the number of layers of platinum-rhodium metal screen was varied. Tests carried out with 10, 21, and 30 layers failed to show any appreciable effect of number of layers on ignition characteristics at the start of each run. However, the 30-layer igniter appeared to be the most durable and to provide the most reproducible results. Figure 11 presents ignition delay¶ for two similar runs, chamber pressure = 5 atm and air temperature = 750°F, using a different igniter in each test. The minimum ignition delay appears to be of the order of 0.1 sec for these conditions. Figure 12 shows the appearance of the igniter after run 4367 as well as the Hastelloy X washers and nuts used to attach the igniter to the flame holder. Typical loss of igniter material by melting is visible in the figure. In subsequent tests only 30-layer igniters were used.

To demonstrate the temperature effect on catalytic ignition, a run was made at a constant combustion chamber static pressure of 5 atm and a fuel-air ratio of 0.030 as shown in Fig. 13. From the figure it is evident that air temperature is a critical variable. Ignition delay increases rapidly from 0.2 sec as the air temperature decreases from 750° toward 700°F. For air temperatures below 695°F, no ignition was obtained. However, it is expected that the temperature limit for ignition would be a strong function of combustion chamber pressure and fuel-air ratio.

Vitiated air runs (without oxygen make-up) were made for air pressures from 7 to 9.0 atm, and ignitions were obtained for air temperatures at the combustion chamber entrance as low as 580°F (Fig. 14). The fuel-air ratio used in Fig. 14 is the combustor fuel flow rate divided by the total air flow rate. No attempt will be made here to correlate these data with the clean air data because of the uncertain vitiation effect. Suffice it to say that the durability of the 30-layer 90% platinum-10% rhodium metal screen igniter was demonstrated for a total burning time of approximately 30 sec at these conditions.

Discussion of Results

As demonstrated in colored movie observations and reproduced in black and white in Fig. 15, successful ignition is preceded by a visible temperature increase of the igniter material. The first sign of a reaction is a visible glow from the igniter material with no appearance of flame. The glow intensity of the igniter increases with time until a visible flame appears at the igniter; then the flame spreads out across the duct, at which time the combustion chamber pressure increases. Although it is uncertain whether the metal screen causes a simple thermal ignition or a more complicated process, it is clear that ignition is related to the increase in catalyst temperature. These observations, coupled with the qualitative description of ignition of hydrocarbon-air mixtures by platinum given by Belles and Swett,[3] led to the use of a simple thermal model to correlate the experimental results. It can be surmised that the heat generated by the catalytic

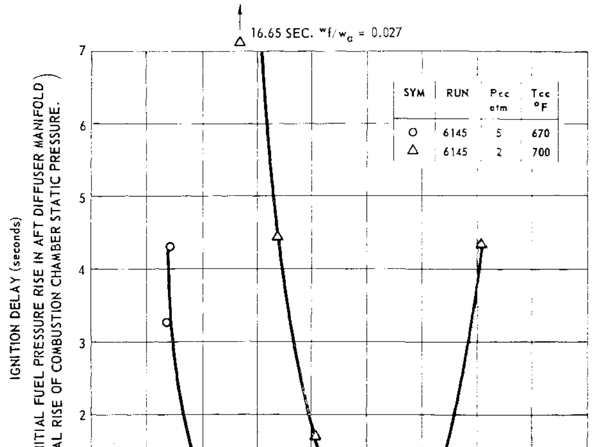


Fig. 10 Ignition delay vs combustor fuel-air ratio; large-scale fuel cooled combustor; 21-layer 90% Pt-10% Rh metal screen igniter downstream of combustor strut; JP-5 fuel.

‡ In the course of full-scale testing it was demonstrated that the catalytic surface became "poisoned" and that a cleaning process was necessary to insure reproducibility. As a result, much of the large-scale work was done with igniters washed in concentrated nitric acid, rinsed in distilled water, and thoroughly dried in an oven.

§ In this test, ignition delay was determined as the difference in time between the rise in fuel pressure in the manifold just upstream of the combustor and the rise in combustion chamber static pressure. Any time required to fill the combustor and struts leads to an uncertainty, e.g., the fuel-air ratio = 0.071 data point had 4.35-sec pressure change ignition delay, whereas movie coverage of the igniter showed 3.03 sec between the first frame having visible igniter glow and the ninety-seventh frame showing flame in the entire duct. From the igniter point of view, any filling time is thereby unfairly added to the ignition delay time because the igniter probably does not "feel" the fuel until the passages are filled. However, the pressure change ignition delay is considered satisfactory to indicate relative effects. More realistic ignition delay times are reported subsequently when improvements in instrumentation application were achieved.

¶ For these and subsequent data, ignition delay is measured from initial fuel injection into the combustion chamber (indicated by a temperature decrease at a thermocouple mounted inside the electrical igniter shroud) to the initial rise in combustion chamber static pressure.

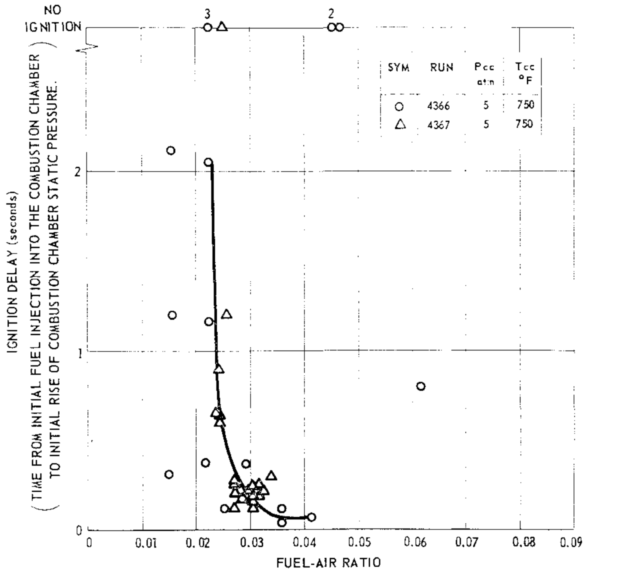


Fig. 11 Ignition delay vs combustor fuel-air ratio for two separate 30-layer 90% Pt-10% Rh metal screen igniters; large-scale fuel cooled combustor; igniter downstream of combustor strut; JP-5 fuel.

process, which takes place on the surface of the igniter screen, raises the temperature of the catalyst. As the temperature of the catalyst increases, the rate of catalysis is thereby increased, leading to a greater rate of heat and active particle generation. Like a chain reaction, this process eventually produces a flame.

On the other hand, any mechanism that succeeds in draining heat from the catalytic process tends to inhibit the transition from initial surface reaction to flame ignition. Two experiments reported previously demonstrate this statement. When, in the sectional tests, the butterfly igniter was insulated from the cooled gutter wall with Rokide Z, the ignition delay decreased from 2.9 to 1.6 sec, and the ignition limits increased from fuel-air ratios of approximately 0.027–0.047 to 0.014–0.054 (see Fig. 7). Also, in sectional tests, it was observed that thicker screen wire led to longer ignition delays and narrower ignition limits. Since the rate of heat generation is proportional to the surface area, and the heat required to raise the temperature of the screen to any particular value is proportional to the mass of the wire, it follows that the use of thicker wire with a lower surface area to mass ratio would

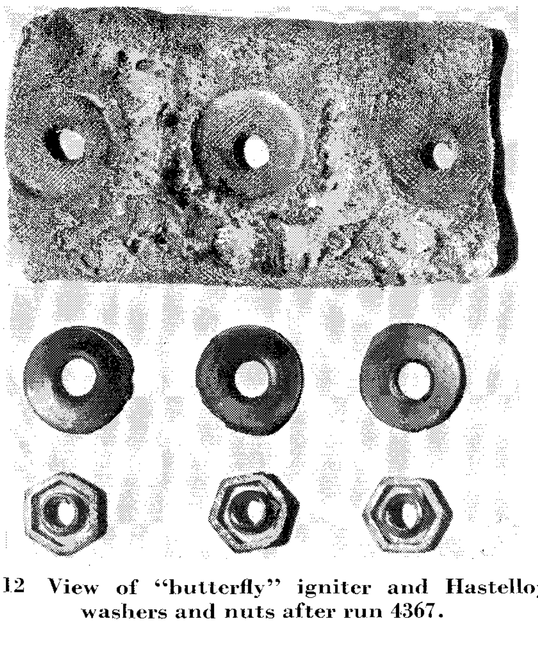


Fig. 12 View of "butterfly" igniter and Hastelloy X washers and nuts after run 4367.

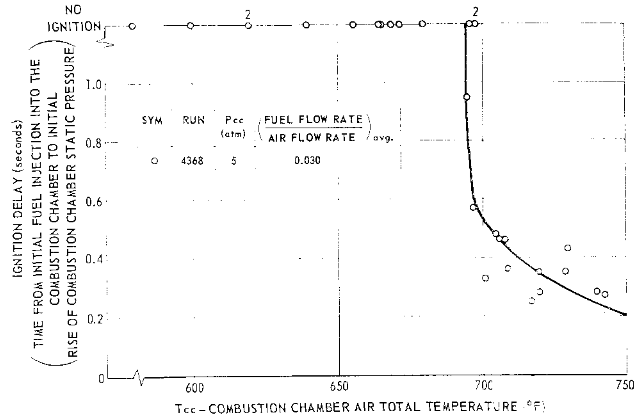


Fig. 13 Ignition delay vs air temperature at constant fuel-air ratio; large-scale fuel cooled combustor; 30-layer 90% Pt-10% Rh metal screen igniter downstream of combustor strut; JP-5 fuel.

result in the longer ignition delays and narrower ignition limits obtained.

Continuing with the simple thermal model introduced previously, one can propose the probable effects of air temperature and pressure. For a given fuel-air ratio, the fuel and oxygen concentration, and therefore the rate of catalysis (heat generation), should be directly proportional to air pressure (air flow rate). Since the rate of heat transfer is proportional to only a fractional power of pressure (0.8 power for turbulent flow), an increase in air pressure should cause a relatively greater increase in heat generated compared to heat loss, and so promote wider limits and shorter ignition delays. Moreover, since radiative heat loss from the igniter is a function only of igniter and sink temperatures, this particular loss would become less significant with increased pressure. The data reported verify the widening of ignition limits (see Fig. 10) as air pressure is increased.

Regarding the effect of air temperature on ignition, one suspects that the catalyst surface must achieve some particular elevated temperature before the local fuel-air mixture reacting on the surface can generate active chemical species and heat at rates sufficient to ignite the remaining mixture. It follows then that the greater the difference between the igniter temperature resulting from hot air flow alone and the igniter temperature at ignition, the more difficult it will be to get ignition. In fact, both at APL and OAL, it was observed that for many test conditions the igniter would heat up rapidly to a given temperature level (e.g., red color) and remain in this state for 10 to 20 sec without further temperature rise and, of course, without engine ignition occurring. Then, for the

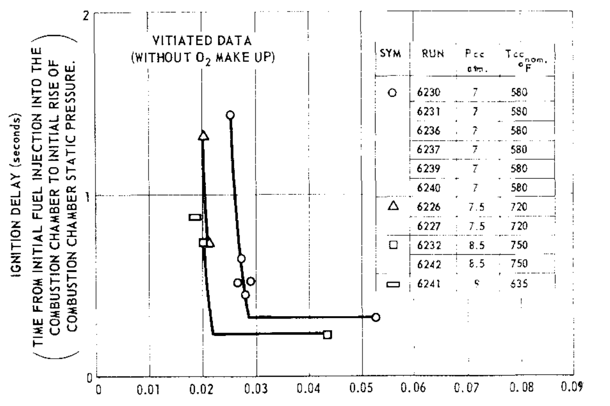
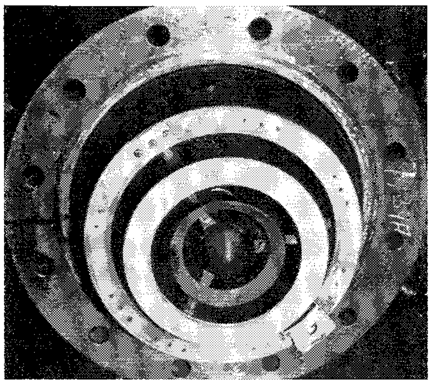
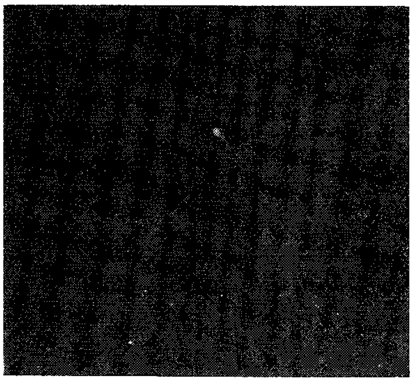


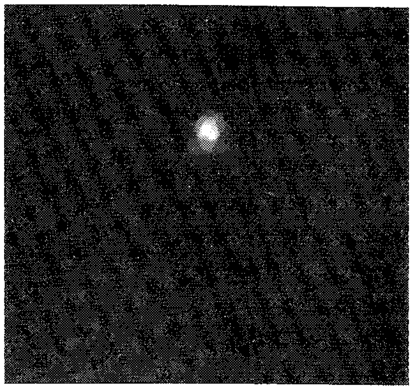
Fig. 14 Ignition delay vs combustor fuel-air ratio; large-scale fuel cooled combustor; 30-layer 90% Pt-10% Rh metal screen igniter downstream of combustor strut; JP-5 fuel.



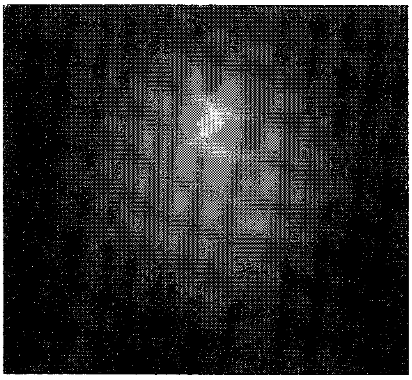
a) View of combustor prior to run 6145; igniter mounted downstream of combustor strut



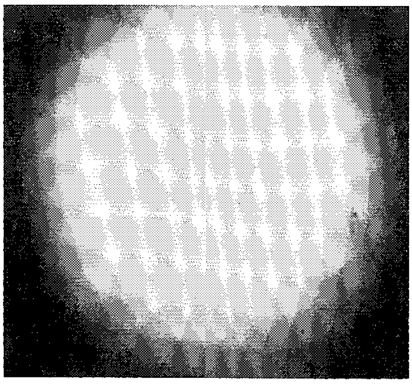
b) 0.94 sec from first evidence of igniter glowing; igniter heating up



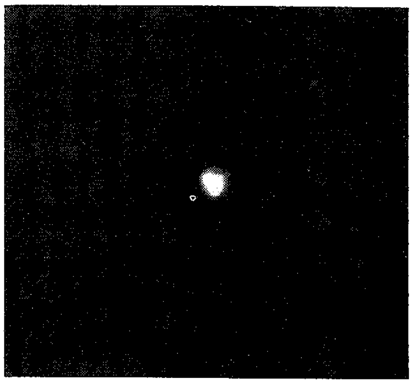
c) 1.03 sec; small flame zone at igniter



d) 3.25 sec; flame spread out across duct



e) 3.97 sec; typical steady burning view



f) 5.75 sec; fuel off, igniter cooling down

Fig. 15 Photographic observations of 90% platinum-10% rhodium metal screen "Butterfly" type catalytic igniter with large-scale ramjet engine baffle combustor; OAL run 6145. p_{cc} = 2 atm; T_{cc} = 700°F; fuel-air ratio = 0.071; camera speed = 32 frames/sec.

same air pressure and fuel-air ratio, the air temperature would be increased (e.g., from 700° to 900°F) and ignition would occur in several seconds. Thus, as illustrated in Figs. 5 and 13, for each air pressure and fuel-air ratio there is a minimum air temperature above which the heat balance is favorable for ignition and below which it is unfavorable.

Coupling these effects of air temperature and pressure, it is found that the minimum ignition temperature decreased as pressure was increased. For example, in the full-scale tests 1200°F was required to provide ignition at 1 atm, whereas at 5 atm 670°F was sufficient. Reference 3 (p. 107) presents a similar effect for the crucible method ignition temperatures of JP-5, 477°F required at 1 atm and 415°F at 5 atm pressure.

The one remaining variable of significance, the fuel-air ratio, must be considered in an even more qualitative way. Since the rate of catalysis is related to both fuel and oxygen concentration, it follows that some particular fuel-air ratios will provide the optimum mixtures for rapid ignition. Such a characteristic is obvious throughout the results presented. However, the significant parameter is the local and not the over-all fuel-air ratio. That is, the vaporized fuel-air mixture in the vicinity of the catalyst must govern the catalytic process. This local ratio, determined by the nature of the air flow, fuel injection, and vaporization, may not be equal to the over-all ratio. Therefore, it must be pointed out that the quantitative effect of over-all fuel-air ratios presented here are specific to the hardware used in these tests, as demonstrated by the different performance of similar igniters in the sectional and full-scale tests. Since the design of the large-scale combustor was fixed by other conditions and the position of the igniter (behind a fuel strut) was selected as described previously, one must accept the local fuel-air ratio prevailing at the igniter.

Had the nature of the program been different, an attempt to determine the relationships among the local fuel-air ratio, air pressure, air temperature, and over-all fuel-air ratio would have been made to provide more basic information needed to design igniters for other configurations. As it is, this work points out the significant parameters and leaves to future designers the opportunity to contribute the more basic data.

Conclusions

The test program discussed in this paper demonstrates that an inexpensive (approximately $40), reliable, catalytic igniter can be developed for use with ramjet engine baffle combustors. It has been shown that increased air pressure and air temperature widen the fuel-air ignition limits, and that increased air temperature decreases the ignition delay time. The effect of over-all fuel-air ratios on ignition characteristics has been shown to be extremely significant, but the actual local conditions for ignition are not established. A simple thermal model is used to correlate the experimental results.

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