Experimental Evaluation of Catalytic Flame Stabilization for Aircraft Afterburners

Catalytic flame stabilization encompasses the use of a porous catalytic surface to initiate, stabilize, and provide a continuous pilot for flame propagation. A preliminary assessment of the feasibility of employing catalytic flame stabilization to the design of flameholders for aircraft afterburners has been completed. Initial testing has demonstrated that catalytic flame stabilization in aircraft afterburners can be achieved. For the non-optimal catalytic flameholders evaluated, smooth light-off and stable operation were obtained; higher combustion efficiencies were measured and higher pressure losses were observed. During the course of the experiment a significant number of design aspects were determined to require further investigation. These design aspects along with other results of this study are discussed in this paper.

INTRODUCTION

Catalytic flame stabilization as applied to aircraft afterburners encompasses the use of a catalytic surface to initiate, stabilize, and provide a continuous pilot for flame propagation. Catalytic flame stabilization differs from traditional catalytic combustion (a heterogeneous process) in that the catalyst is used only to "bootstrap" the fuel-air mixture to temperature and species conditions such that gas phase reactions can predominate; the balance of energy release is accomplished through homogeneous chemical processes.

Previous analytical studies (1,2) conducted at the Air Force Aero Propulsion Laboratory have indicated that an afterburner performance advantage can be realized by employing catalytic flame stabilization in aircraft afterburners. These studies projected the performance advantages of reduced flameholder pressure drop and/or increased afterburner combustion efficiency. Other potential benefits included improved ignition capability and reduced acoustic instability (high frequency "screech" and low frequency "rumble").

The purpose of this paper is to present the results of an experimental test program to verify previous analytical results. The intention of this investigation is to provide basic information for a preliminary assessment of the catalytic flameholder concept. The primary objectives for this study were:

a) To determine the performance characteristics (combustion efficiency and pressure drop) of the catalytic flameholder relative to conventional bluff body flameholders.

d) To determine the operational system parameters which might indicate problems with the concept.

ADVANTAGE OF CATALYTIC FLAME STABILIZATION

Conventional afterburners typically release 85% to 95% of the available chemical potential while main burners routinely release 99%. The poorer afterburner performance is attributable to the high speed of flow, which approaches 250 meters/sec (820 ft/sec). The practical restriction of afterburner lengths results in a short residence time and thus incomplete combustion. Faster reaction rates would enhance the axial rate of energy release. If the accelerated change of combustion efficiency is achieved, the designer could choose either higher performance or decreased hardware length (Figure 1). That is, if...
current lengths are acceptable, a performance increase associated with an improved efficiency would result ($\Delta n_e$). Alternatively, if the current performance level is acceptable, it could be achieved at a shorter length, $L'$. It is not possible to precisely predict the length saving without a measurement of the combustion efficiency. However, because of the expected asymptotic approach to high levels of efficiency, the length reduction should be substantial.

Another implication of the high speed flow in the afterburner is that the flameholder, which pilots and establishes the reactions, must be narrow in order to avoid unacceptable pressure drop. Therefore, the combustion originates from a few small sources (one to three flameholder rings) and, because of the high velocity, spreads at angles on the order of $7^\circ$.

A minimum afterburner length would be the distance necessary to completely fill the cross section with reaction—that is, the distance at which the combustion zones merge. Larger sources for flame propagation would proportionally reduce the required afterburner length. The designer would have the option of shorter hardware length or increased system performance for a given length (Figure 2).

One means to achieve the benefits of a larger flameholder, without imposing unacceptable pressure losses, is to consider using a porous body instead of a solid body. This design would permit flow through as well as around the device, producing less pressure drop than a conventional bluff body of equal dimensions. Therefore, the porous body could be made wider, reaping the benefits of reduced length or increased performance. In essence, this approach could be termed "toward a flat flame afterburner," for such a design would ensure maximum energy release in minimum lengths. The ideal case of completely filling the combustor cross section with a porous flameholder may not be attainable, however, because of the associated pressure loss.

It is recognized that replacing the bluff body stabilizer with a porous device alone is not acceptable. A conventional flameholder successfully stabilizes the overall combustion processes by providing a continuous pilot for the spreading combustion wave. The recirculating wake flow behind the solid body provides shear layer residence times the same order as the characteristic chemical reaction times, and thus establishes the required piloting phenomenon.

The porous stabilizer does not provide a similar piloting zone. The flow through the body tends to wash out the recirculating, and hence piloting, character. This problem can be corrected by making the device catalytically active. In this case, the reactants passing through it would be substantially oxidized in a manner similar to a catalytic main burner. Since the afterburner is always accompanied by a military mainburner mode, it always receives hot inlet gases. This condition removes the low inlet temperature problem that plagues the application of catalyst to mainburners. The high inlet temperature increases the reaction rates, offsetting the problem of decreased catalyst contact time due to the high velocities. Note that complete oxidation of the internal mixture is not a requirement. The degree of reaction would be chosen to produce a stabilizing wake of hot combustion species similar to that existing behind a bluff-body device. Thus, the desired flame stabilization should be achievable using catalytic, porous bodies which would initiate the combustion over a combustor cross section greater than a conventional device of equal pressure loss.

**CATALYTIC FLAMEHOLDER DESIGNS**

The flameholder designs evaluated in this program consisted of catalytically coated and uncoated annular honeycomb rings as shown in Figure 3. Each annular ring was composed of twelve pie-shaped ceramic segments formed into a wagon-wheel design as illustrated in Figure 4. During fabrication each ceramic segment was compressively loaded in the radial direction by using inner and outer layers of woven metal to permit differential thermal expansion. Retention of the ceramic segments was accomplished by use of inner and outer stainless steel retaining rings as shown in Figure 5.
The ceramic materials used in the fabrication of the catalytic flameholder designs were cordierite (2M₆O·2Al₂O₃·5SiO₂) and silicon nitride (Si₃N₄). Cordierite is an aluminum-magnesia-silica ceramic used extensively for automotive catalytic converters. It is thermally stable with a temperature limitation of approximately 1200°C (2200°F). An example of the thin wall, square pore cordierite honeycomb material is shown in Figure 7.

Silicon nitride is a high strength refractory receiving consideration for turbine blade applications. It also displays excellent thermal shock resistance as well as a high temperature capability. Its maximum temperature limitation is 1900°C (3450°F). The silicon carbide test material fabricated with thick walls and circular pores is shown in Figure 8. The physical dimensions of both substrate materials are given in Table 1.
Table 1. Catalytic Flameholder Descriptions

<table>
<thead>
<tr>
<th>SUPPORT MATERIAL</th>
<th>CELL SIZE (mm)</th>
<th>VOID AREA (%)</th>
<th>RING SIZE (m)</th>
<th>L/D</th>
<th>BLOCKAGE (%)</th>
<th>CATALYST TYPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>CORDIERITE</td>
<td>1.3</td>
<td>64</td>
<td>0.356 x 0.213 x 0.025</td>
<td>20</td>
<td>28</td>
<td>Pt/Pd</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.356 x 0.213 x 0.051</td>
<td>40</td>
<td>26</td>
<td>Pt/Pd</td>
</tr>
<tr>
<td>SILICON NITRIDE</td>
<td>2.3</td>
<td>46</td>
<td>0.356 x 0.213 x 0.051</td>
<td>22</td>
<td>36</td>
<td>Pt/Pd</td>
</tr>
<tr>
<td>MODIFIED</td>
<td>2.3</td>
<td>42</td>
<td>0.356 x 0.213 x 0.051</td>
<td>24</td>
<td>38</td>
<td>Pt/Pd</td>
</tr>
</tbody>
</table>

The catalytic coating of ceramic substrate materials was performed by Oxy-Catalyst of West Chester, Pennsylvania. Prior to catalytic impregnation, an alumina wash coat was applied to the substrate surface. The wash coat was then impregnated with a noble metal catalyst consisting of two parts palladium (Pd) to one part platinum (Pt). Catalyst mass loading was 3.6 grams total metals per liter of treating solution.

During the course of the test program, several of the silicon nitride disks were modified to prevent flameholder deterioration during sustained operation. The modified design was identical to the original flameholder design except that four 6 mm (1/4-inch) cooling holes were drilled in each pie-shaped ceramic segment and a 3 mm to 6 mm (1/8-inch to 1/4-inch) band of high temperature ceramic cement was applied to the disk's outer perimeter. The purpose of this cement was to block the flow of the high temperature reaction gases in the vicinity of the disk's outer retainer ring. A modified silicon nitride disk is shown in Figure 9.

The test equipment consisted of a J85-GE-5 engine, a sea level test stand, and a gas sampling system and data acquisition system. The J85 is an afterburning turbojet engine consisting of an eight-stage, axial-flow compressor directly coupled to a two-stage turbine, an annular combustor, an afterburner (A/B) and a variable-area exhaust nozzle. The engine is rated at 12,900 newtons (2680 pounds) thrust at military power and 17,100 newtons (3850 pounds) thrust at max afterburner power.

The J85 afterburner assembly consists of a diffuser section housing the flameholder, a cylindrical double-walled annular burner section, and a variable area exhaust nozzle as shown in Figure 10. Details of the diffuser section are shown in Figure 11 and the individual diffuser components are shown in Figure 12. The fuel injection system includes four pilot and 16 main burner fuel spray bars. Operation of the J85 afterburner is controlled as a function of the power lever angle.
EXPERIMENTAL APPROACH

The general approach used in this feasibility study was to obtain and compare the afterburner performance of a J85-5 turbojet engine using a conventional bluff body flameholder to that of the same engine using catalytically-active flameholders. Data were acquired in this study to evaluate afterburner flame stabilization limits, ignition capability, imposed total pressure drop, and combustion efficiency. Combustion efficiency was determined by integration of point emission measurements. Pressure drop was determined by measurement of total pressure upstream and downstream of the flameholder. Flame stability and ignition capability were determined. The flameholder designs examined in this study were evaluated under the full range of afterburner operating conditions stated in Table 2.

Table 2. Test Condition Summary

<table>
<thead>
<tr>
<th>TEST CONDITION</th>
<th>FUEL FLOW (kg/hr)</th>
<th>FUEL/AIR RATIO</th>
<th>ADIABATIC FLAME TEMPERATURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>MILITARY</td>
<td>---</td>
<td>0.016</td>
<td>700°C</td>
</tr>
<tr>
<td>MIN A/B</td>
<td>910</td>
<td>0.030</td>
<td>1100°C</td>
</tr>
<tr>
<td>MID A/B</td>
<td>1590</td>
<td>0.039</td>
<td>1400°C</td>
</tr>
<tr>
<td>MAX A/B</td>
<td>2270</td>
<td>0.048</td>
<td>1700°C</td>
</tr>
</tbody>
</table>

At each test condition, a random sequence of four to six complete data sets were obtained to characterize each flameholder design. Although complete data sets were obtained for the conventional hardware design at all power conditions, hardware constraints limited the data obtained with the catalytic flameholder to the military and MIN A/B test conditions.

In preparation for a test run, the J85 engine was stabilized at the appropriate test condition. The emissions probe was then traversed horizontally across the exhaust plane approximately 0.2 meters (8 inches) downstream of the exhaust nozzle and on a line passing through the center of the engine. The sampling technique used was the equal area approach with the exhaust plane divided into eleven equal areas (3). At each probe position 28 test parameters were recorded on magnetic tape for subsequent data reduction. Test parameters obtained at each probe location included inlet total and static pressures, mainburner and afterburner fuel flows, flameholder inlet total pressures, exhaust exit total pressure, and exhaust gas emissions. A complete listing of recorded test parameters is given in Table 3.

EXPERIMENTAL TEST RESULTS

Initial testing was oriented toward obtaining baseline performance data with the conventional J85 bluff body flameholder over the full range of afterburner operating conditions listed in Table 2. During those tests, both flameholder combustion efficiency and pressure loss were measured. Following baseline testing the conventional J85 flameholder and ignitor were removed and the pilot burner manifold plugged. A catalytic flameholder was then installed.

Light-off of the catalytic flameholder was achieved by advancing the power lever angle from military power to approximately 454 kg/hr (1000 lb/hr).
<table>
<thead>
<tr>
<th>CHANNEL NUMBER</th>
<th>PARAMETER NAME</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Exhaust Gas Temperature</td>
</tr>
<tr>
<td>2</td>
<td>Inlet Temperature</td>
</tr>
<tr>
<td>3</td>
<td>Main Fuel Flow</td>
</tr>
<tr>
<td>4</td>
<td>A/B Fuel Flow</td>
</tr>
<tr>
<td>5</td>
<td>NO/NOX</td>
</tr>
<tr>
<td>6</td>
<td>CO</td>
</tr>
<tr>
<td>7</td>
<td>Total Hydrocarbons</td>
</tr>
<tr>
<td>8</td>
<td>CO2</td>
</tr>
<tr>
<td>9</td>
<td>H2</td>
</tr>
<tr>
<td>10</td>
<td>X Probe Position</td>
</tr>
<tr>
<td>11</td>
<td>Y Probe Position</td>
</tr>
<tr>
<td>12</td>
<td>Nozzle Position Indicator</td>
</tr>
<tr>
<td>13</td>
<td>R.P.M.</td>
</tr>
<tr>
<td>14</td>
<td>Inlet Diff. Pressure #1</td>
</tr>
<tr>
<td>15</td>
<td>Inlet Diff. Pressure #2</td>
</tr>
<tr>
<td>16</td>
<td>Inlet Diff. Pressure #3</td>
</tr>
<tr>
<td>17</td>
<td>Inlet Diff. Pressure #4</td>
</tr>
<tr>
<td>18</td>
<td>Inlet Total Pressure #1</td>
</tr>
<tr>
<td>19</td>
<td>Inlet Total Pressure #2</td>
</tr>
<tr>
<td>20</td>
<td>Inlet Total Pressure #3</td>
</tr>
<tr>
<td>21</td>
<td>Inlet Total Pressure #4</td>
</tr>
<tr>
<td>22</td>
<td>Thrust</td>
</tr>
<tr>
<td>23</td>
<td>Probe Total Pressure</td>
</tr>
<tr>
<td>24</td>
<td>Ambient Pressure</td>
</tr>
<tr>
<td>25</td>
<td>A/B Inlet Pressure #1</td>
</tr>
<tr>
<td>26</td>
<td>A/B Inlet Pressure #2</td>
</tr>
<tr>
<td>27</td>
<td>A/B Inlet Pressure #3</td>
</tr>
<tr>
<td>28</td>
<td>A/B Inlet Pressure #4</td>
</tr>
</tbody>
</table>

A/B fuel flow. If ignition was not observed (audibly or visibly) within 10 sec, the ignition attempt was considered a failure.

Since the exact catalyst bed length required for stable ignition was not known, a trial-and-error approach was adopted. Test results for various L/D ratios for the cordierite flameholder design representing a 28% annular blockage are shown in Table 4 for the military power test condition. These results indicate light-off at L/D ratios of 60 and 80. However at high L/D ratios (L/D = 80), reaction rates increase to the point that reaction temperature exceeds material limitations and results in immediate localized substrate failure as shown in Figure 13.

### Table 4. Pressure Drop/Light Off Comparison

<table>
<thead>
<tr>
<th>FLAMEHOLDER</th>
<th>PERCENT PRESSURE DROP *</th>
<th>LIGHT OFF</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONVENTIONAL</td>
<td>4.77</td>
<td>YES</td>
</tr>
<tr>
<td>CORDIERITE Pt/Pd COATED</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L/D = 20</td>
<td>7.62</td>
<td>NO</td>
</tr>
<tr>
<td>L/D = 40</td>
<td>9.08</td>
<td>NO</td>
</tr>
<tr>
<td>L/D = 60</td>
<td>10.71</td>
<td>YES</td>
</tr>
<tr>
<td>L/D = 80</td>
<td>11.80</td>
<td>YES</td>
</tr>
</tbody>
</table>

* At Military Power Condition

**Fig. 13. Damaged Cordierite Flameholder (L/D = 80)**

Further testing was directed toward obtaining catalytic combustion efficiency and pressure drop data at actual afterburner operating conditions with the cordierite disk having an L/D = 60. During this testing, it was revealed that although successful light-off could be easily achieved, sustained catalytic flameholder operation could not be maintained because of deterioration of the outer stainless steel retaining ring (Figure 5), which secures the catalytic substrate segments, and because of deterioration of the substrate itself. Figure 14 shows the extent of flameholder damage resulting from several unsuccessful attempts to obtain sustained flameholder operation at MIP A/B fuel flow rates. Because of apparent material limitations, further testing with the catalytic cordierite flameholder designs was not pursued.

**Fig. 14. Damaged Cordierite Flameholder (L/D = 60)**

Pressure drop data, expressed as percent, for the conventional J85 flameholder designs are compared to cordierite flameholder designs as a function of L/D in Table 4. The data in Table 4 are based on "cold flow" (no fuel flow to the afterburner) pressure measurements taken at the military power test condition.
At this condition, the conventional flameholder imposed a 4.77% pressure loss. For the same condition, the successful (with respect to light-off capability) cordierite flameholder designs imposed pressure losses of 9.08% and 11.80%. In order to determine the effect of pressure drop on light-off capability, a test was also conducted on a cordierite disk that was not catalytically active. This test was to confirm that gas flow changes associated with high pressure drop across the cordierite flameholder could not initiate or sustain combustion. An uncatalyzed cordierite flameholder arrangement having an L/D = 80 failed to spontaneously ignite the flammable afterburner gas mixture.

Having exhausted test variables utilizing the cordierite designs, testing was continued with the silicon nitride flameholder designs. An L/D of 44 was the largest that could be achieved from construction of the available silicon nitride test articles. In testing this arrangement, immediate spontaneous ignition (1 to 3 sec) was again achieved at low A/B fuel flow rates. However, upon increasing the fuel flow to the MIN A/B power condition, flameholder degradation was again observed. Unlike the cordierite design, damage to the more thermally stable silicon nitride flameholder was limited to the stainless steel retaining ring. It was hypothesized that this damage was being caused by hot gas recirculation zones induced by flow around the outside of the flameholder. To overcome this problem, a small redesign effort was initiated. The objectives of this effort were twofold. The first was to reduce the proximity of the hot reaction gases to the flameholder outer ring. The second was to increase the cooling flow in the region near the flameholder retainer ring. The first objective was accomplished by plugging the two honeycomb channels nearest the flameholder retainer ring. The second was accomplished by drilling 6 mm (1/4-inch) cooling holes in the catalyst substrate. The redesigned silicon nitride flameholder is shown in Figure 9.

The redesigned flameholder also demonstrated satisfactory ignition and sustained low power afterburner operation (i.e., less than MIN A/B power). In the first attempt to achieve the MIN A/B power condition, ignition of catalytic flameholder was accomplished within 2-5 seconds at an afterburner fuel flow of 540 kg/hr (1200 lb/hr). After several minutes of stable operation at this condition the A/B fuel flow was increased rapidly in a 1-2 second time period to MIN A/B. Immediate deterioration of the flameholder was apparent by the observation of sparks in the exhaust plume. Upon shut-down and examination, little actual damage was evident. A small section, approximately 6 mm diameter, of the stainless steel retaining ring had been burned out.

Based on the above observations, a second attempt was made to achieve the MIN A/B test condition. During this attempt, it was felt that a more gradual increase in A/B fuel flow would result in achievement of the MIN A/B power condition without flameholder deterioration. This was indeed the case. After A/B ignition at 780 kg/hr (1750 lb/hr) A/B fuel flow, a slow transition to MIN A/B produced successful, sustained operation for 30 minutes.

The data obtained at this condition are compared to conventional J85 flameholder performance in Table 5. The catalytic flameholder did result in a marked increase in combustion efficiency at MIN A/B while developing a much larger pressure drop than the conventional flameholder.

Table 5. Efficiency Comparison

<table>
<thead>
<tr>
<th>FLAMEHOLDER</th>
<th>PERCENT PRESSURE DROP *</th>
<th>AFTERBURNER EFFICIENCY (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONVENTIONAL</td>
<td>7.37</td>
<td>83.3</td>
</tr>
<tr>
<td>MODIFIED</td>
<td>83.3</td>
<td>89.6</td>
</tr>
<tr>
<td>SILICON (L/D = 44)</td>
<td>83.3</td>
<td>89.6</td>
</tr>
</tbody>
</table>

* At MIN A/B Power Condition

Following the successful operation of the catalytic flameholder at MIN A/B, an attempt was made to obtain data at the MID A/B power condition. During this test, the engine was operated for 17 minutes at military power before transitioning to A/B operation at 635 kg/hr (1400 lb/hr) A/B fuel flow. After approximately 5 minutes of operation at the MIN A/B power condition, the A/B fuel flow was increased slowly to 1225 kg/hr (2700 lb/hr). This condition was maintained for approximately 3 minutes without any problems. The A/B fuel flow was gradually increased over a 20 to 30 second period to the MID A/B test condition of 1600 kg/hr (3500 lb/hr) fuel flow. This power level was maintained for only 10 to 15 seconds before apparent flameholder deterioration resulted.

Inspection of the catalytic flameholder revealed that small sections of the stainless steel retaining ring were burned out and warped in several places. Small sections of cement had also been melted away. Based on these observations, it was concluded that a large portion of the aft side of the flameholder had been close to the melting point of the stainless steel frame.

Several subsequent unsuccessful attempts were made to obtain stable operation at the previously obtained MIN A/B power condition. In the first attempt light-off could not be achieved with an A/B fuel flow of 545 kg/hr over 20 sec. In the second attempt unstable ignition was achieved at slightly higher A/B fuel flow after a 15 to 20 sec duration. The A/B fuel flow was increased to the MIN A/B condition for the next two attempts. Ignition again resulted after about 15 sec. In both cases severe uncontrolled oscillations in afterburner combustion system were encountered and the tests aborted. Inspection of the flameholder following the four unsuccessful tests revealed no further flameholder damage. Figure 15 depicts the final condition of this flameholder.

**DISCUSSION OF RESULTS**

The catalytic flameholder results presented in the previous section have demonstrated that catalytic flame stabilization in aircraft afterburners can be achieved. For the non-optimum catalytic flameholder designs evaluated, good light-off and stable flameholder operation were obtained; higher combustion efficiencies were measured; and higher pressure losses were observed. These results indicated both positive and negative effects. A more in-depth understanding of these effects can be achieved by examining each performance parameter in the context of the experiment in which they were obtained.
The "cold flow" pressure drop measurements at military power for the conventional and catalytic flameholder designs are given in Table 6. Pressure losses for the various catalytic flameholder designs range from 10.71% to 16.77%. Pressure loss for the conventional J85 hardware was 4.77%.

The higher pressure losses of the catalytic flameholders can be attributed to several factors. The first of these concerns the location of the flameholder within the J85 engine. Figure 11 depicts the J85 afterburner diffuser assembly. This figure vividly illustrates the complex and interrelated aerodynamic designs of the conventional J85 flameholder and J85 afterburner diffuser.

The catalytic flameholders were designed to make maximum use of the existing flameholder attachment hardware. As such, the catalytic flameholders were located within the variable cross section area of the afterburner diffuser rather than a more preferred location within the constant cross sectional area of the afterburner casing. This design compromise obviously contributed to the high pressure losses induced by the catalytic flameholders.

Combustion Efficiency
Combustion efficiency data obtained for the catalytic flameholder designs were extremely limited. Essentially, only one data point was obtained for afterburner operation due to limited availability of test hardware - that of the modified silicon nitride flameholder at MIN A/B power. Table 5 compares the combustion efficiency and pressure losses of the catalytic flameholder to that of the conventional J85 flameholder at the MIN A/B test condition. The data from Table 5 indicates that the catalytic flameholder offers a substantial efficiency improvement over a conventional J85 flameholder. This encouraging result, however, must be tempered by the fact that the catalytic flameholder also resulted in over twice the pressure loss observed with the conventional flameholder design.

The pressure loss consideration is particularly important because of its influence on all modes of engine operation, not just the afterburner mode (4). However, as discussed previously, the higher pressure losses associated with the catalytic flameholders evaluated under this program are not necessarily an inherent deficiency of the catalytic flameholder concept in general or of the concept's application to aircraft afterburners. The data of Table 5 are encouraging in that it shows that higher afterburner combustion efficiency can be achieved with the catalytic flame stabilization concept. There is no data to show that an equally high value of combustion efficiency could not be achieved with more acceptable pressure drop.

Table 6. Pressure Loss Comparison

<table>
<thead>
<tr>
<th>L/D</th>
<th>AFTERBURNER BLOCKAGE (%)</th>
<th>PERCENT *</th>
<th>LIGHT-OFF</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONVENTIONAL FLAMEHOLDER</td>
<td>--</td>
<td>36</td>
<td>4.77</td>
</tr>
<tr>
<td>CORDIERITE FLAMEHOLDER DESIGN</td>
<td>60</td>
<td>28</td>
<td>10.71</td>
</tr>
<tr>
<td>SILICON NITRIDE FLAMEHOLDER DESIGN</td>
<td>44</td>
<td>36</td>
<td>15.35</td>
</tr>
<tr>
<td>REDESIGN SILICON NITRIDE FLAMEHOLDER</td>
<td>44</td>
<td>38</td>
<td>16.77</td>
</tr>
</tbody>
</table>

* At Military Power Condition
Light-Off Capacity

The conventional J85 flameholder, fabricated from sheet metal, has a parabolic cross section. Inlet ducts, which supply a controlled fuel/air ratio to the flameholder interior to pilot combustion, are positioned at four locations on the upstream side of the annulus (Figure 12). Light-off of the pilot burner is accomplished by a spark ignitor positioned within the annulus.

Light-off of the catalytic flameholder is relatively straightforward and requires no spark ignitor. Furthermore, for the catalytic flameholders examined in this program, the use of pilot spray bars were not required. This reduction of system hardware is in itself an important advantage of the catalytic flameholder.

As stated in the Experimental Test Results, light-off with the catalytic flameholder was accomplished simply by increasing the afterburner fuel flow to 545-680 kg/hr. Ignition with the conventional hardware on the other hand, requires activation of the afterburner ignitor and A/B fuel flow. Ignition with the catalytic flameholder was in general much smoother than with the conventional flameholder. Furthermore, once ignition was obtained the catalytic flameholder operated with remarkable stability in spite of its crude design.

Although the catalytic flameholder exhibited excellent steady state operation, its transient operation was very poor. As described in the test results, changes in power setting had to be performed gradually over extended periods of time ranging from 10 to 30 seconds. Again, this result can be primarily attributed to the catalytic flameholder's crude design, its non-optimum location within the afterburner diffuser, and the use of the conventional J85 main spray bars rather than a more optimum fuel atomization scheme.

Other Observations

Probably the most severe limitation of the catalytic flameholder concept is the inability of the catalytic flameholder to function over the entire range of afterburner operating conditions. The cause of this phenomenon is believed to be due to rapid catalyst deactivation at afterburner operating conditions above MIN A/B. Since the detailed chemical analyses required to determine the exact deactivation mechanism were beyond the scope of this study, the specific mechanism is unknown. Other catalytic combustion studies, however, have identified the following deactivation mechanisms:

1) Volatilization of active metals from the substrate surface as a function of catalyst constituents and operating temperature.

2) Loss of active metal surface area caused by catalyst sintering or poisoning phenomenon.

3) Loss of BET surface area resulting of occlusion of active metal in the pores of the washcoat.

4) Loss of active materials by attrition due to poor washcoat adhesion.

The active metal catalyst used in this study was a platinum/palladium catalyst. Platinum oxide formed by the surface oxidation of platinum is known to exhibit a significant vapor pressure at temperatures above 1200°C (2200°F). As seen in Table 2, this temperature between the MIN and MID A/B power conditions. Based on the above, it may be concluded that the most probable cause of the catalyst deactivation observed in this study was due to the volatilization at the active metal catalyst components. Catalyst sintering may also have been a contributory factor.

The catalytic materials evaluated in this study were prepared in early 1977 and as such were first generation oxidation catalysts. A significant increase in the understanding of the preparation of stable noble metal catalysts has taken place since that time. For example, grain stabilization, the codeposition of certain stabilizing oxides or their precursors with an active metal solution, has been found to be an effective method for minimizing the volatilization of active metals. Sintering temperatures can be increased by forming alloys with higher melting point metals or by formation of intermetallics. The use of alloy intermetallics also lowers the catalyst's potential for volatilization. The control of particle size distribution is still another method of catalyst improvement for minimizing the loss of active metal due to sintering or poisoning.

The development of high temperature, rare earth oxide (e.g. lanthanum and cerium oxide) catalysts are also currently taking place. The NASA High Temperature Durable Catalyst Development Program is aimed at developing a 1427°C (2600°F) catalyst. Programs such as this offer the highest potential for solution of the high temperature catalyst deactivation problem.

CONCLUSION

A preliminary assessment of the catalytic flame stabilization concept for aircraft afterburners has been completed. Initial testing has demonstrated that catalytic flame stabilization in aircraft afterburners can be achieved. For the non-optimum catalytic flameholders evaluated, smooth light-off and stable operation were obtained; higher combustion efficiencies were measured; and higher pressure losses were observed.

During the course of the experiment a significant number of design aspects were determined that require further investigation. Paramount among these aspects is the need for a controlled investigation of the trade-offs between combustion efficiency and flameholder pressure drop; the need for development of improved fuel/air distribution techniques; and the need for development of more thermally stable catalyst and monolith materials.

RECOMMENDATIONS

Based on the encouraging results of this study, it is recommended that a more controlled experimental test program be conducted to investigate the design trade-offs between combustion efficiency and pressure loss. The primary objective of this program should be to develop a fundamental understanding of the aerothermochemistry of catalytic flame stabilization and to establish design aids to be used in subsequent exploratory development efforts.

The fundamental information derived from this investigation should include characterization of the flow field surrounding a catalytic flameholder, characterization of the role of the catalyst in stabilizing the combustion processes (including wake recirculation, turbulent shear layer combustion, and downstream flame propagation), quantification of stability limits, evaluation of instability and acoustic wave abatement, investigation of liquid fuel impingement on the catalytic flame surface, and the determination of approach flow, approach temperature, and fuel/air ratio gradient effects. Finally, the above studies should include...
the investigation of both "graded cell" (5,6) and uniform cell substrate designs.

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REFERENCES


