Development of an Innovative High-Temperature Gas Turbine Fuel Nozzle

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ABSTRACT

The objective of the Innovative High-Temperature Fuel Nozzle Program was to design, fabricate, and test propulsion engine fuel nozzles capable of performance despite extreme fuel and air inlet temperatures. Although a variety of both passive and active methods for reducing fuel wetted-surface temperatures were studied, simple thermal barriers were found to offer the best combination of operability, cycle flexibility, and performance. A separate nozzle material study examined several nonmetals and coating schemes for evidence of passivating or catalytic tendencies. Two pilotless airblast nozzles were developed by employing finite-element modeling to optimize thermal barriers in the stem and tip. Operability of these prototypes was compared to a current state-of-the-art piloted, prefilming airblast nozzle, both on the spray bench and through testing in a can-type combustor. The three nozzles were then equipped with internal thermocouples and operated at 1600°F air inlet temperature while injecting marine diesel fuel heated to 350°F. Measured and predicted internal temperatures as a function of fuel flow rate were compared. Results show that the thermal barrier systems dramatically reduced wetted-surface temperatures and the potential for coke fouling, even in an extreme environment.

I. Introduction

To meet the U.S. Department of Defense IHPTET (Integrated High Performance Turbine Engine Technology) program goal of doubling current aircraft propulsion capability by year-2000, future military gas turbines must demonstrate both higher thrust-to-weight ratios and lower specific fuel consumption. Commercial aircraft operators, facing increased fuel costs and stiff competition, share this desire for reduced weight and higher efficiency. Military and commercial interests will also expect improved reliability and maintainability from their advanced engines. The reliability of these powerplants will depend, in part, on fuel injection systems that resist coke fouling in spite of the higher combustor inlet temperatures and heat loadings required for increased performance. The provision of fuel flexibility for the military, and the option of lower-cost, heavy distillate commercial fuels further increases the potential for coking. Another complication is the trend toward use of the fuel as a heat sink for cooling the airframe, avionics, and the powerplant itself, resulting in higher fuel temperatures at the nozzle inlet. The specific goals of the program, which are summarized in Table 1, drive the technical challenges outlined in Figure 1.

Work was divided into four tasks over the course of the three-year effort. The Concept Identification/Evaluation Task employed a literature search to characterize the fuel thermal decomposition process and identify coke-resistant and coke-tolerant materials and technologies. A screening process and detailed evaluation of the most promising techniques then followed. Two candidates were selected for the Detailed Design Task at the end of the first task. Fuel nozzles representing the two finalists were detailed and manufactured during the second task. The Nozzle Performance Testing Task compared both candidates to a current state-of-the-art nozzle design. Spray quality measurements and nozzle performance

| Table 1. Fuel Nozzle Design Criteria. |
| Parameter | Goal |
| Combustor Inlet Temperature | 1600°F |
| Fuel Temperature at Nozzle | 350°F |
| Fuel Types | JP-5, Marine Diesel (DFM) |
| Combustor Performance | Meet or Exceed Current Levels |
| Stability (LBO), Ignition, Combustion Efficiency, Exit Temperature Profile | Throughout Flight Envelope |
| Applicable Engine Cycle | Turboprop, Turbo-shaft (All) |

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Eight materials, including four metals (two of them treated) and four ceramics were chosen: 1. SS316, a corrosion-resistant stainless steel often used in fuel systems, was a baseline. 2. SS416, a harder stainless steel, is used in portions of the nozzle that require erosion resistance. 3. A second SS416 sample was passivated by exposure to hydrogen sulfide—of the nozzle that require erosion resistance. 4. A second SS416 coupon was passivated by exposure to hydrogen sulfide—of the nozzle that require erosion resistance. 5. Teflon. 6. MACOR, a machinable silica-based ceramic. 7. LAS (lithium-aluminum-silicate) a crystallized glass with very low thermal conductivity. 8. Fused silica, a widely available amorphous glass, with good high-temperature strength and insulating properties.

Rectangular coupons approximately 5 inches long, 0.300 inch wide, and 0.125 inch thick, were fashioned out of each material. A groove 0.185 inch wide and 0.050 inch deep was machined down the center of each coupon to carry the hot fuel. Surface roughness in the groove, measured in the flow direction, was 22 micro-inches/1-inch for the metal coupons, and ranged from 6 for the fused silica to 17 for the MACOR. All eight coupons were sandwiched between the halves of an SS307 block, equipped with fittings to conduct fuel through the groove in the coupons. A gasket prevented leakage from the block and communication between the coupons.

Marine diesel fuel (DFM) with a JPTOT breakpoint temperature of 400°F was used for the evaluation. Fuel was heated to 540°F by passage through a coil of aluminum tubing immersed in a barrel of thermal fluid maintained at 550°F by electric heating elements. The sample holder was maintained at 540°F by an electric heater, and heavily insulated to ensure uniform temperatures throughout. Fuel residence time in the aluminum heating coil was approximately 25 seconds; the Reynolds' number for fuel inside the coil was above 10,000. Fuel residence time across the samples was 0.54 second. The local bulk velocity was 0.75 ft/sec, and the Reynolds' number, based on the channel dimensions, was 1000. The fuel pressure was maintained at 75 psia to prevent boiling. The samples were exposed for 22 hours.

The coupons were dried and carefully weighed prior to the test, and the reflectance at one end in and the middle of each groove was measured using an optical densitometer. The coating ranged from hazy coffee-stain-like deposits on the SS316 and the ceramic materials to jet-black 'sandbars' on the SS416. The quantitative results appear in Table 2. Based on the weight change of the SS416, site of the heaviest deposits, a coking rate of just over 20 micro-grams/hr-sq cm was observed. This is consistent with measurements quoted in Reference 3 for a wetted-surface temperature of 540°F.

The following conclusions were drawn from the evaluation. First, none of the materials tested out-performed SS316, a previously proven coke-resistant material. Second, coking rates for the ceramics were nearly equivalent to those for SS316. With regard to coking alone, these materials can be used interchangeably. A similar result for both metals and nonmetals suggest that surface chemistry plays a limited role when no outright catalysts are present. This implies that coating or otherwise changing the surface of such materials will not be effective, at least in the temperature and flow range studied.

III. Detailed Design

The Simplex-Airblast Prototype

A cross section of the simplex-airblast design is shown in Figure 2. Atomization is accomplished by using a swirling flow of high-velocity air to shatter the conical fuel sheet emitted from a high-flow simplex tip, combining two widely used techniques in a single-circuit pilotless design. The airblast allows larger contamination-tolerant passages to be used in the simplex part of the nozzle, and improves patterning at high power settings. The thorough fuel/air mixing and other familiar benefits of airblast atomization are also realized. The smallest fuel passage dimension in this simplex-airblast is more than three times the minimum commonly found in pilots nozzle. Despite the large passages, the simplex portion of the nozzle is still capable of producing an 'onion' or 'tulip' structure at very low fuel pressure drops.

**Figure 1. Future Propulsion Engine Fuel Nozzles Will Encounter Severe Coking Environment.**

Tests in a high-pressure combustion rig were conducted. Finally, the internal temperature distribution for both candidates and the baseline nozzle were measured as a function of fuel flow rate by operating each nozzle at the conditions outlined in Table 1. Following is a detailed discussion of each task.

II. Concept Identification/Evaluation

The purpose of this task was to gather information on the basics of the coke deposition process, as a foundation for gathering deposit-resistant and/or deposit-tolerant technology and materials. This information was summarized by assembling a number of nozzle concepts, each employing one or more of the techniques identified, for further analysis. A screening process then identified the two concepts most likely to satisfy all of the program goals.

The concept identification phase of the program also included an investigation of coking properties for several engineering materials. Although similar studies were identified in the literature (References 1, 2) little data was available for recently developed passivation techniques and coatings in general, and ceramics in particular. This study attempted to identify a material for use in the wetted portion of the nozzle that would inhibit thermal breakdown of the fuel and/or discourage adhesion of solids formed in the freestream. Ceramic materials, thought to be of some value for their low conductivity and emissivity, were also checked for evidence of either passivating or catalytic properties.

Eight materials, including four metals (two of them treated) and four ceramics were chosen: 1. SS316, a corrosion-resistant stainless steel often used in fuel systems, was a baseline. 2. SS416, a harder stainless steel, is used in portions of the nozzle that require erosion resistance. 3. A second SS416 sample was passivated by exposure to hydrogen sulfide-doped helium at high temperature, a process developed for treating oil refinery components. 4. A third SS416 sample was coated with EYMYD, a fluorinated polyamide similar to Teflon. 5. PSZ (partially stabilized zirconia), a tough ceramic with low conductivity (1.3 Btu/ft-hr-F), and a thermal expansion rate similar to metals. 6. MACOR, a machinable silica-based ceramic. 7. LAS (lithium-aluminum-silicate) a crystallized glass with very low thermal conductivity. 8. Fused silica, a widely available amorphous glass, with good high-temperature strength and insulating properties.
Figure 2. The Simplex-Airblast Prototype Combines Two Proven Forms of Atomization, Multiple Air Gap Thermal Protection.

Typical of ignition conditions. This is an advantage over purely prefilming nozzles.

A multiple air-gap thermal barrier insulates fuel-wetted surfaces in the simplex-airblast prototype, both in the stem and tip regions. Use of the air gap, which allows a relatively simple all-metal construction, was suggested by an analysis of several approaches to fuel-stem insulation. GED’s F125-GA-100 afterburning turbofan nozzle (baseline) was used for the stem geometry and length. This nozzle and the F125-GA-100 combustion system are described in Reference 4. An eight-point engine cycle, consistent with the flight envelope of an advanced turboshaft engine, was derived for the analysis, with 350°F fuel and 160°F air inlet temperatures at the design point. A cycle pressure ratio of more than 50:1 was required to obtain the desired combustor inlet temperature of 1600°F. This cycle is similar to those envisioned for future generations of the Joint Technology Advanced Gas Generator (JTAGG) program. The conditions studied gave a fuel Reynolds number range from 1700 to 137,000, and an external air flow Reynolds number range from 34,000 to 324,000. Fuel properties were for JP-5.

One-dimensional radial heat flow, and steady-state, constant-properties flow of both the fuel and air were assumed. In addition to the baseline case, the effect of increasing the gap between fuel-carrying tubes and the outer heat shield was investigated, both for the plain air-gap case, and with insulating materials inserted in that gap. Two excellent insulators, Carborundum's Fiberfrax (k=1.29 Btu-in/hr-ft²°F) and Manville's Min-K (k=0.37 Btu-in/hr-ft²°F at 1200°F) were selected for the analysis.

Figure 3 plots the total resistance of the fuel stem as a function of stem outer diameter for the three different barriers studied at two cycle points. The dashed lines are for a high-altitude, high-Mach number dash point, with combustor inlet temperature of 1600°F. The solid lines are for a subsonic cruise condition with inlet temperature of 700°F. The effectiveness of the air gap is comparable to that for the Fiberfrax insulation, but it deteriorates as the inlet temperature increases due to the increased radiative exchange between the outer heat shield and fuel tube through the air gap. Air gap conductivity is an effective value, based on both thermal conduction through the air and radiative exchange between the concentric cylinders. The Fiberfrax insulation is only marginally better than an air gap at the baseline stem dimensions, and the insulation is actually less effective for some stem diameters. Min-K, however, out-performed the air gap for the conditions studied. Generally speaking, insulator conductivity at or below 0.50 Btu-in/hr-ft²°F is required to consistently better the effectiveness of a practical air gap. Another factor favoring air gaps is the dramatic reduction of effectiveness that both insulators suffer when contaminated with water, fuel, or other liquids.

<table>
<thead>
<tr>
<th></th>
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<td>19.6479</td>
<td>19.6487</td>
<td>0.08</td>
<td>14.8</td>
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<td>-48.65%</td>
<td>22</td>
<td>Haze of Coke</td>
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<td>SS316 EYMYD</td>
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<td>19.5495</td>
<td>1.9</td>
<td>8.9</td>
<td>4.5</td>
<td>-49.44%</td>
<td>22</td>
<td>Dark Streaks</td>
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<td>SS416</td>
<td>18.9841</td>
<td>18.9877</td>
<td>3.6</td>
<td>9.5</td>
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<td>-63.16%</td>
<td>23</td>
<td>Uniformly Black</td>
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<td>SS416 Passiv</td>
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<td>18.7634</td>
<td>0.9</td>
<td>1.7</td>
<td>22</td>
<td>Patchy Black</td>
<td>7</td>
<td></td>
<td></td>
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<tr>
<td>LAS</td>
<td>6.0745</td>
<td>Broke</td>
<td>--</td>
<td>66.6</td>
<td>31.5</td>
<td>-52.70%</td>
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<tr>
<td>SIO</td>
<td>5.3728</td>
<td>Broke</td>
<td>--</td>
<td>6.9</td>
<td>6.1</td>
<td>-11.59%</td>
<td>6</td>
<td>Stained</td>
<td>3</td>
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<tr>
<td>MACOR</td>
<td>6.162</td>
<td>Broke</td>
<td>--</td>
<td>58.7</td>
<td>27.2</td>
<td>-53.66%</td>
<td>17</td>
<td>Stained</td>
<td>4</td>
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<tr>
<td>PSZ</td>
<td>14.7169</td>
<td>14.7179</td>
<td>1.0</td>
<td>48.4</td>
<td>28.5</td>
<td>-51.12%</td>
<td>15</td>
<td>Stained</td>
<td>2</td>
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</tbody>
</table>

Figure 3. Air Gaps Can Be an Effective Thermal Barrier to Heat Absorption in the Injector Stem.
The Ceramoblast Prototype

Figure 4 shows an annotated cross section of the second prototype. This nozzle is a single-circuit airblast design that uses both air gaps and monolithic ceramic insulating materials to protect fuel-wetted parts. The well-established prefilming technique (Reference 5) is used to produce a high-quality hollow cone spray. Recirculation zones and other stagnant spots in the fuel side of the nozzle that would contribute to deposit formation have been eliminated in the distributor by avoiding the sharp transitions, annular manifolds, and cross-drilling often found in these parts. Each passage is a continuous, smooth conduit from the stem exit to the prefilmer entrance, represented by the long crosses in the diagram.

The thermal protection scheme devised for the ceramoblast employs two of the monolithic ceramics studied in the materials experiment, PSZ and LAS. LAS is used for the inner heat shield because of its low coefficient of thermal expansion in comparison to the surrounding metal parts. PSZ is used for the outer heat shield because its coefficient of expansion is compatible with aerospace steels. Standoffs were machined into the metal parts, minimizing the contact between the insulation and fuel distributor, and providing air gaps on either side. An air gap was also placed between the prefilming lip and outer shell.

Location of insulation inside the nozzle was suggested by thermal studies of the baseline nozzle tip, and a generic prefilming pure-airblast tip similar to the ceramoblast design. A pseudo-three-dimensional model of both tips was generated, including all conduction paths, fuel and air convection, and the effect of flame radiation. The finite-element model of the nozzle tip was generated using an in-house quasi-3D thermal analyzer code. Axisymmetric elements allowed conduction in two directions and nonaxisymmetric elements were thermally linked in the tangential direction assuming a half-width conduction length. Additional convection faces were assigned to axisymmetric elements which bordered nonaxisymmetric elements. The boundary conditions were assumed to be convective everywhere except at the combustor-facing portion of the nozzle, where a flame radiation boundary condition was applied using a standard nonluminous flame correlation. The isotherms calculated are representative of the temperature midway circumferentially between the nonaxisymmetric elements. An instrumented baseline nozzle was operated in a combustion rig to verify the model predictions.

The baseline nozzle’s excellent performance in rig and engine testing, and similar size and application to that envisioned for the two prototypes, made it a logical candidate for comparison throughout the program. The baseline nozzle employs a prefilming airblast secondary circuit (flow number = 18) for operation above idle throttle settings, and a pressure-swirl pilot (flow number = 2) for starting. (Flow number equals fuel flow [pph] divided by the square root of the pressure drop.) A cross section of the nozzle tip is shown in Figure 5, beside a mirror-image contour plot of the predicted temperatures for an engine idle condition. Measured temperatures are also indicated in the figure, and compare favorably with the predicted values.

The contour plot provides a useful illustration of the distribution of heat energy and potential coking sites in the tip. Study of the baseline nozzle suggested that the two major sources of energy absorption in the nozzle were the air swirl vanes and any surface exposed to the flame. At an altitude cruise point, for example, the predicted heat flux entering the nozzle face from flame radiation is more than 20 times that absorbed by conduction and convection through the stem. The frontal area observing the flame is thus a key element in nozzle thermal loading. Although the fuel temperature rise amounted to less than 20 degrees from inlet to exit for the worst case, surfaces in the secondary circuit rose significantly above the fuel temperature.

A second modeling effort was conducted using a generic prefilming, pure-airblast tip, very close to the configuration that eventually became the ceramoblast nozzle. Simplified two-dimensional axisymmetric geometry was employed to allow numerous combinations of materials to be studied. Figure 6 illustrates the major components of the concept and predicted temperature contours for the case where the fuel-carrying portion of the nozzle tip is a low-conductivity monolithic ceramic. The boundary conditions for the plot are from the altitude cruise point, with 1608°F combustor inlet temperature. Several conclusions that applied to the ceramoblast design were drawn from this study. In the generic stem/tip attachment scheme, the stem protection system, either an air gap or an insulating material, was terminated upstream of the stem/tip interface, for ease of manufacture. The modeling effort showed that the stem protection scheme must be brought down into the tip area to avoid conducting heat from...
Results of these thermal studies are reflected in the ceramoblend design. Although monolithic ceramics are used to avoid the possibility of fuel contamination associated with the Fiberfrax and Min-K materials, air gaps supplement both ceramic elements. A double air gap is employed in the stem and between the metallic prefilmer and outer case. The metallic distributor is joined directly to the fuel-carrying inner tube; the stem inner heat shield continues into the tip. The outer heat shield is captured from the flange end of the stem and does not contact the tip. A single air swirler, made as small as possible, is placed at the extreme end of the tip. The vanes are undercut at the hub to further reduce conduction from the air cap. Frontal area of the fuel-carrying parts is minimized. The ceramoblend and simplex-airblast nozzles are compared in Figure 7.

IV. Nozzle Performance Testing

The purpose of this task was to determine the spray quality of the two prototypes over a significant operating range, and to determine the impact on operability of the single-circuit, coke-tolerant designs by operating both prototypes and the baseline nozzle in a high-pressure combustion rig. Flow number, spray cone angle, patternation, and mean drop size were measured over a significant range of air-pressure drops and fuel-flow rates. Spray measurements were performed using a Malvern Model 2600 instrument. Both standard MIL-C-7024 (1) and cold (12 centistoke viscosity) calibrating fluids were used. The flow number is 18 for the ceramoblend nozzle and 15 for the simplex-airblast. The atomizer is installed in a plenum box which allows the pressure drop across the airside of the nozzle to be measured and varied. The nozzle is installed vertically, spraying downward into a vented drain. The simplex-airblast prototype is shown installed in the spray booth in Figure 8.
Following the spray testing, each nozzle was evaluated for combustor performance. The scope of the program prevented tests in a full-scale, multiple nozzle, high-pressure burner rig. Since only a single nozzle system could be tested, a can liner was modified to accept the prototypes and baseline nozzles. The dome has been modified to accept an axial swirler that co-rotates with both the dome louvers and the nozzle swirlers. A schematic of the rig is shown in Figure 10. The fuel nozzle slip-fits through the dome swirler at the tip end and, using a metal compression gasket, bolts to an engine-plenum-style flange. Although the can had little in common with the full-annular system of an advanced demonstrator engine, the nozzle tested concurrently has a long history in both full scale rig and engine tests. Comparison with this nozzle is thus a key link to the environment for which the prototypes were designed. The lean-stability, exit-temperature pattern factor and the combustion efficiency were measured for each of the cycle conditions summarized in Table 3 during the first sequence of tests, using both the JP-5 and DFM fuels. The reference velocity used in Table 3 is based on the can combustor flow area and on the gas inlet temperature, pressure, and flow rate. The loading parameter is defined in Figure 11.

The rig was equipped with multi-point thermocouples and kiel probes to measure inlet and exit pressures and temperatures. A propane-fired preheater set immediately upstream of the liquid-fueled can was used to achieve the 160°F inlet temperatures. A water-cooled back-pressure valve was used to set rig pressure. Micro-Motion mass-flow sensors were used to measure the fuel flow rates.

### Table 3. Combustion Rig Test Conditions.

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Design, SLS</th>
<th>Cruise</th>
<th>Idle, SLS</th>
<th>Alt, Decel</th>
<th>Ignition</th>
<th>Ignition</th>
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<tr>
<td></td>
<td></td>
<td>MCP, 10K, M=0.3</td>
<td>SLS</td>
<td>20K, M=0.7</td>
<td>16K, M=0.2, 10% N</td>
<td>25K, M=0.2, 15% N</td>
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<td>WA3, lb/sec</td>
<td>3.975</td>
<td>2.930</td>
<td>1.520</td>
<td>0.936</td>
<td>0.136</td>
<td>0.137</td>
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<td>T3, F</td>
<td>500°F</td>
<td>444</td>
<td>208</td>
<td>185</td>
<td>-55°F</td>
<td>-52°F</td>
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<tr>
<td>P3, psia</td>
<td>133.0</td>
<td>95</td>
<td>41.0</td>
<td>23.72</td>
<td>8.20</td>
<td>5.60</td>
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<td>ΔP/P, percent</td>
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<td>5.04</td>
<td>5.51</td>
<td>6.64</td>
<td>0.68</td>
<td>1.51</td>
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<tr>
<td>Wf, pph</td>
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<td>171</td>
<td>50</td>
<td>25</td>
<td>20</td>
<td>20</td>
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<tr>
<td>EGT, °F</td>
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<td>1525</td>
<td>866</td>
<td>727°F</td>
<td>—</td>
<td>—</td>
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<tr>
<td>Far, total</td>
<td>0.0175</td>
<td>0.0162</td>
<td>0.0091</td>
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<td>0.675</td>
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<td>1.64</td>
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<tr>
<td>VRef, ft/sec</td>
<td>81</td>
<td>78.4</td>
<td>69.8</td>
<td>71.6</td>
<td>18.9</td>
<td>28.1</td>
</tr>
</tbody>
</table>

Figure 9. Candidates Demonstrate Good Spray Quality in Spite of Single-Circuit Design.

Air/liquid ratio is the same for both nozzles at each pressure drop, since the air-flow area is identical. The 12-centistoke fluid does not have a significant impact on spray quality for either nozzle. As expected, the more complex prefilming technique produces the finest spray at all pressure drops. With no air flow, the simplex tip still produces an open spray cone; the ceramoblast does not.
chill the fuels to the 12-centistoke point for cold-ignition tests. A methanol/dry-ice slurry was used to
measure fuel flow. Air flow was measured across standard ASME orifice sections. A methanol/dry-ice slurry was used to
chill the fuels to the 12-centistoke point for cold-ignition tests. Combustion efficiency was calculated from a carbon
balance by sampling the exhaust using industry standard nondispersive infrared analyzers for CO and CO2, and a flame
ionization detector for UHC. The gas sample was drawn through the rig exit pressure measuring ports.

Combustion efficiency and lean blowout fuel/air ratio are plotted against aerodynamic loading (Figure 11) for both
prototypes and the baseline nozzle. Lean stability and combustion efficiency for the prototypes is similar to that for the
piloted nozzle, in spite of the much finer atomization available at low fuel flows with the baseline nozzle pilot. The
highest stability and combustion efficiency was measured for the ceramoblast because it combines fine atomization with a
very wide spray angle. The DFM's lower volatility is reflected in the generally higher fuel/air ratios required to keep the
combustor alight, but neither prototype shows a particular sensitivity to the fuel type.

The pattern factor results (Figure 12) show more distinct differences. Sharp peaks in the patternation measured during
bench testing of the simplex-airblast nozzle are reflected in its high pattern factor. The ceramoblast nozzle also showed
higher pattern factor than the baseline nozzle at low fuel/air ratios, but improved to a comparable value at the higher
cruise throttle setting. The pattern factor for both nozzles could be adjusted, in practice, by varying both the spray angle
and combustor aerodynamics.

Ignition tests were conducted by presetting the desired inlet conditions and fuel flow, then diverting fuel from a chilled
circulating loop into the combustor as soon as the ignitor was switched on. Steady increase in the exit temperature within
five seconds was considered a successful light. A single igniter plug is used, with a spark rate of three per second and
four joules per pulse. Ignition fuel/air ratio vs. aerodynamic loading is plotted for the three nozzles in Figure 13. Although
both prototypes required higher fuel/air ratios for ignition than did the piloted nozzle at the same loading, the range of
operation for the simplex-airblast nozzle is roughly equivalent to the baseline design. Results for the ceramoblast were
disappointing, given its excellent lean stability and finer spray quality. Similar experience (good stability, atomization
quality, yet poor ignition) with other single-circuit, pure airblast prefilming nozzles in a variety of combustion systems
suggests that some common characteristic of these nozzles may be at fault. The tendency of fine drops to be carried
through the combustor primary zone and away from the igniter by the central atomizing air stream has been suggested as one
explanation. Of the parameters checked, ignition characteristics are perhaps the most context-sensitive. Additional devel-
lopment would obviously be required to match the piloted ignition envelope with these single-circuit nozzles.

V. High Temperature Testing

Each prototype was operated with hot JP-5 and DFM fuels at the 1600°F air inlet temperature and 350°F fuel inlet tempera-
ture condition. Internal temperatures were measured for both fuels over a range of flow rates. An in-line propane-fired
preheater provided 1.6 lb/sec of vitiated air at 1600°F. Liquid fuel was supplied to the nozzle inlet at 350°F. The liquid-

![Figure 11. Lean Blowout and Combustion Efficiency Measured for Prototype Nozzles Compares Favorably to Baseline Performance.](image)

![Figure 12. Exit Temperature Profile for Tested Nozzles Shows Some Patternation Variation.](image)

![Figure 13. Ignition Results Using Cold Fuel Show That Single-Circuit, Pure Airblast Designs Require Higher Fuel/Air Ratio During Start Than Does Piloted Nozzle.](image)
fueled combustor pressure drop was 5.4 percent at an inlet pressure of 60 psia. Fuel flow was varied between 20 and 60 pph. This test point combines a fuel flow consistent with an idle throttle setting with a takeoff inlet temperature and combustor pressure drop for the most severe thermal loading. The high pressure drop increases the air velocity and convective flow through the nozzle swirlers, while the low fuel flow minimizes the cooling effect of liquid. Primary zone equivalence ratio at this point is near 1.0, increasing the radiation loading on the nozzle face.

Both prototypes and a baseline nozzle were equipped with thermocouples for the test. These Chromel-Alumel junctions were installed at strategic locations in the stem and tip during assembly of the nozzles. In addition to wetted-part temperatures, fuel temperature at the nozzle flange and at the entrance to the tip was measured to gauge the temperature rise through the stem. Fuel pressure, flow, and temperature at the nozzle, as well as rig pressure and inlet temperature, were continuously recorded on strip charts. The test nozzle was purged with nitrogen during lightoff of the preheater, and when shutdown was necessary.

Maximum wetted-wall temperatures and fuel temperature rise through the stem are plotted against fuel flow rate for all three nozzles in Figure 14. Considering the severity of the inlet conditions, the wetted-surface temperatures measured indicate the effectiveness of the thermal barrier systems developed. Maximum wall temperatures were 518°F and 473°F for the simplex-airblast and ceramoblast nozzles, respectively. Figure 15 compares measured and predicted temperatures in the ceramoblast tip. The large gradients across the insulation and air gaps were accurately predicted. Good agreement between measured and predicted values on the air gap show that the vane convection and flame radiation terms are correctly modeled. However, the temperature rise in both stems was underestimated by some 25 percent. Although some variation can be attributed to uncertainty in dimensions and other boundary conditions, consistent over-prediction for both stems suggests that one or more of the assumptions in the analysis is flawed. Conduction through the flange into the fuel-carrying tube, which was left out of the original one-dimensional analysis, is the suspected heat source. A simple low-conductivity seal between the mounting flange and plenum, or an internal barrier between the flange and fuel-carrying tube, would effectively block this conduction path.

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