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SPONTANEOUS IGNITION IN AFTERBURNER SEGMENT TESTS AT AN INLET TEMPERATURE OF 1240 K AND A PRESSURE OF 1 ATMOSPHERE WITH ASTM JET-A FUEL

by Donald F. Schultz and J. Robert Branstetter

Lewis Research Center
Cleveland, Ohio 44135

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16. Abstract
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SUMMARY

A brief testing program was undertaken to determine if spontaneous ignition and stable combustion could be obtained in a jet engine afterburner operating with an inlet temperature of 1240 K and at a pressure of 1 atmosphere with ASTM Jet-A fuel. A 49-centimeter-diameter duct with three horizontally mounted water-cooled fuel spraybars was used. No V-gutters or other flame-holding devices other than the spraybars were used. Inlet conditions of 10.4 newton per square centimeter inlet total pressure, 152.5 meter per second inlet velocity, 1240 K inlet total temperature, and oxygen depleted to 14 percent by vitiation of the air supply were used for all tests. The fuel-air ratio was held constant at 0.01 for all tests. Spontaneous ignition with 100-percent combustion efficiency and stable burning was obtained.

INTRODUCTION

This report presents experiences encountered with spontaneous ignition at a 1240 K inlet temperature and a 1-atmosphere pressure with ASTM Jet-A fuel. Previous tests, which used a film vaporizing V-gutter type afterburner, have demonstrated a tendency for spontaneous ignition (ref. 1). Spontaneous ignition and afterburner fuel coking problems were also encountered during the development of the GE4 engine (refs. 2, 3, and 4). The unclassified, nonproprietary data in these references applicable to the spontaneous ignition problems are reproduced in the appendix.

Spontaneous ignition occurs as a function of flame temperature, inlet air temperature, delay time, oxygen content, fuel-air ratio, pressure, and fuel type. Reference 5 indicates the minimum flame temperature for spontaneous ignition for many hydrocarbon fuels. Reference 6 gives information concerning delay time as a function of inlet air temperature, oxygen content, fuel-air ratio, and pressure. A locally very rich mixture with short residence time and vaporization cooling reduces the likelihood of spontaneous ignition. When a film vaporizing V-gutter type afterburner was used, spontaneous ignition occurred when the fuel-air ratio was inadvertently reduced to near 0.005 while operating at a 1255 K inlet air temperature (ref. 1). This condition resulted in rapid destruction of the V-gutter.

References 5 and 6 indicate that at afterburner inlet conditions of 1240 K inlet temperature, 14-percent remaining oxygen, and 1-atmosphere pressure, spontaneous ignition should occur in about 1.5 milliseconds. This assumes an inlet temperature reduction of 30 K from the vaporization of fuel necessary to provide the minimum flame temperature of 1642 K (ref. 5). Calculations indicate this requires a minimum local fuel-air ratio of 0.013. Thus, at these inlet air conditions a minimum local fuel-air ratio of 0.013 must exist at the point where each fuel molecule is 1.5 milliseconds after entering the air stream for ignition to sustain itself.

The tests described in this report were undertaken to determine more about the nature and combustion efficiency of spontaneously ignited combustion at afterburner conditions. The tests were conducted in a 49-centimeter-diameter circular test section with three water-cooled fuel spray bars extending across the test section without additional flame stabilizers. For these tests, the afterburner inlet conditions were held constant at a pressure of 1 atmosphere with an afterburner inlet temperature of 1240 K. The air was vitiated by heating the air with a gasoline fueled combustor having an inlet temperature of 460 K (corresponding to a flight Mach number of approximately 2.4). The afterburner inlet velocity was 152.5 meters per second, and all tests were conducted with an afterburner fuel-air ratio of 0.01 using ASTM Jet-A fuel.

FACILITY

A diagram of the test facility is presented in figure 1. The combustion air was first heated to 460 K in a tube-type heat exchanger and metered with an orifice. A choked butterfly valve located upstream of the test section regulated the flow, and a perforated cylinder dispersed the air into the inlet plenum. After passing through the vitiating preheater and afterburner test section, the gas was quenched and the average temperature measured. Finally, the gases were further quenched and exited through an exhaust butterfly valve into the altitude exhaust system.

ASTM Jet-A fuel was supplied to the afterburner through a conventional system containing flowmeters, a throttle valve, and a positive shutoff valve. Another fuel system provided gasoline to the vitiating preheater.

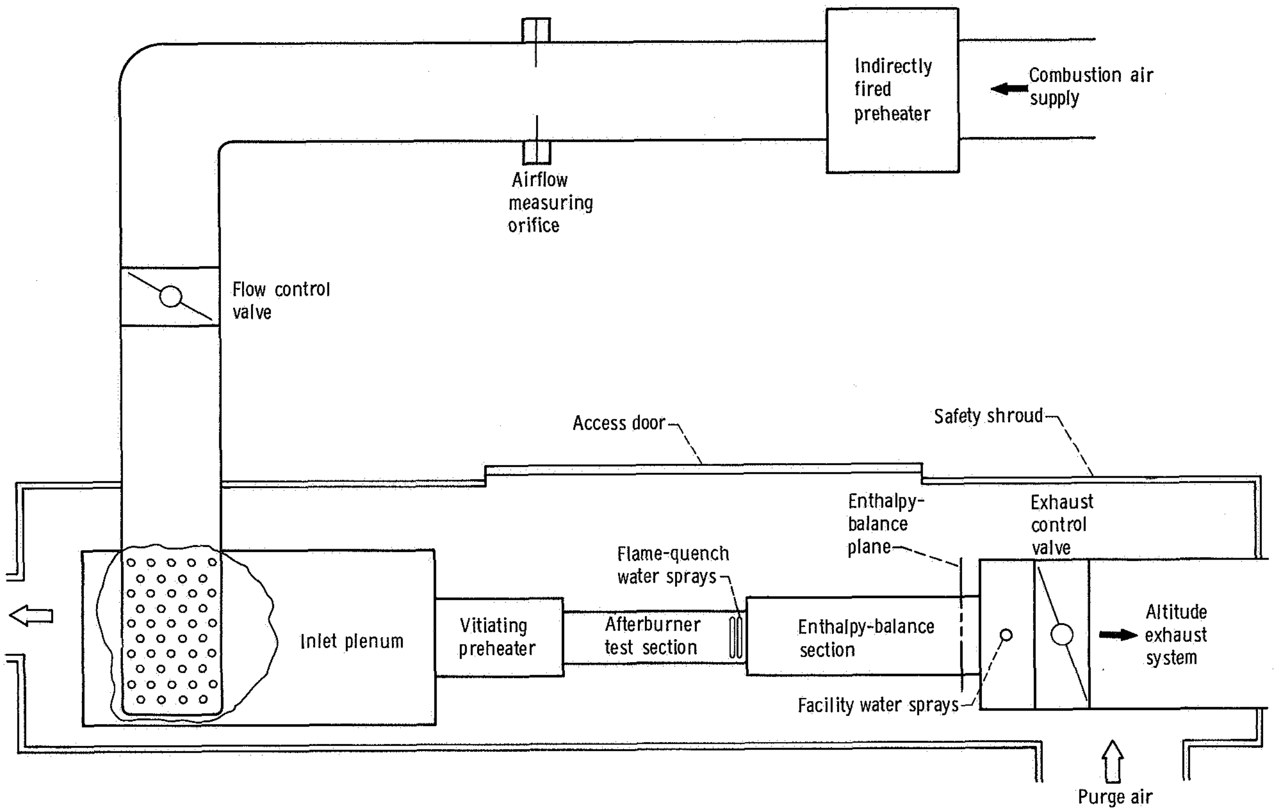


Figure 1. - Schematic diagram of afterburner test facility.

Pertinent details of the afterburner test section are shown in figure 2. The flame-quench water sprays were directed normal to the gas flow. The combustion chamber length, defined as the distance from the downstream face of the spray bars to the flame quench plane, was set at 94 centimeters. The chamber diameter was 49.0 centimeters, and the test afterburner reference area (cross-sectional duct inlet area) was 1878 square centimeters. Further details of the hardware can be found in figures 1 and 2.

Thermocouple rakes were located at the exit of the enthalpy balance section (fig. 1). These instruments and other fixed-position sensors are described in reference 7. Dynamic pressure transducers were flush-mounted on the duct walls with diaphragms exposed to the gas flow in order to detect the presence of pressure oscillations. Data from the steady-state instrumentation were recorded by the laboratory's automatic data recording and processing system. A portion of the instrumentation was connected to an analog computer which provided a continuous display in the control room of airflow rate and fuel-air ratio.

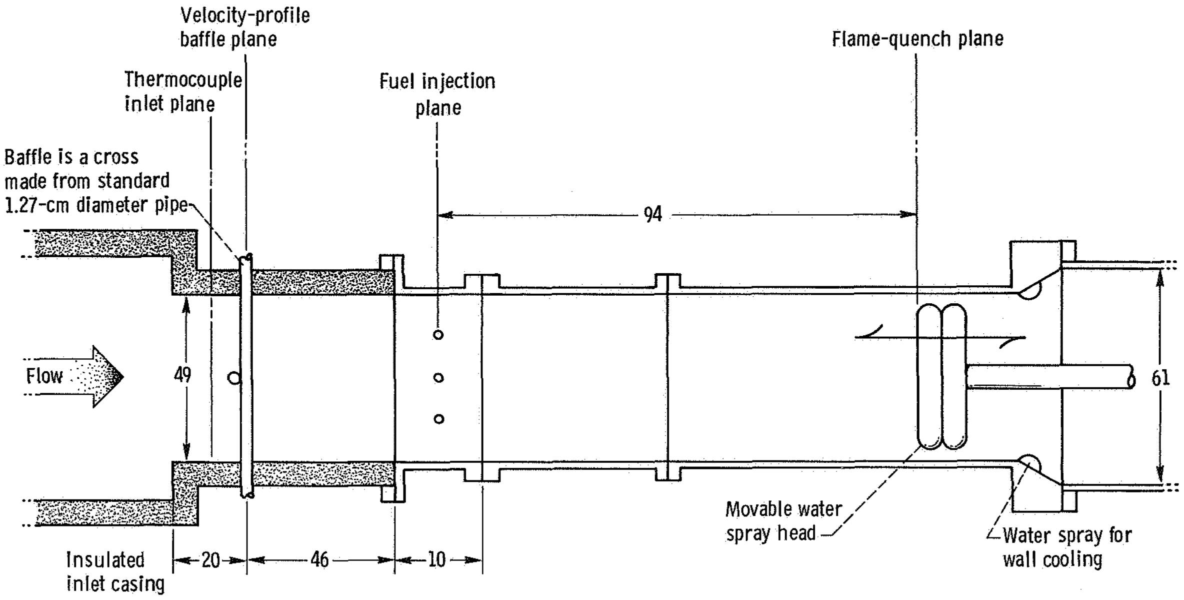


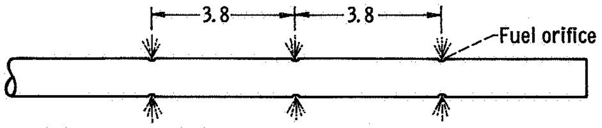
Figure 2. - Cross-sectional view of afterburner test section. Dimensions are in centimeters.

TEST HARDWARE

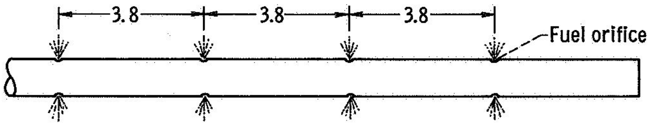
The hardware consisted of three water-jacketed spraybars as shown in figure 3. The spraybars acted as flameholders, so common V-gutter type flameholders were not needed.

The fuel spraybars were water jacketed to minimize the possibility of plugging the fuel tubes due to coking the fuel on the tube walls. Appendix A presents General Electric Company's experiences with fuel tube plugging on their GE4 supersonic transport engine afterburner development program. On an aircraft, the fuel spraybars would have to be fuel cooled rather than water cooled. Since the most severe deposit buildup in the fuel tubes occurs when fuel first enters a hot tube, fuel should be flowing continuously through the cooling jacket so long as an afterburner start is anticipated. Immediately following afterburner shutdown the fuel tubes and cooling jackets should be completely purged of fuel to prevent the buildup of deposits.

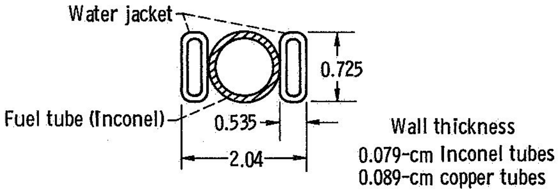
The overall afterburner length from upstream side of the spraybars to the end of the combustion zone was 96 centimeters. The spraybars injected the fuel perpendicular to the airflow. The spraybars were made of Inconel tubing. Two of the spraybars used Inconel tubing for the water jacket while the other, one of the two side spraybars, used a copper tubing jacket. High temperature silver solder was used to provide a good conductive path for cooling the fuel tube. Figure 3 gives a detailed description of the spraybars. Each fuel tube contained an internal thermocouple to measure fuel temperature. The thermocouple was located one-third of the distance from the end of the fuel tube. All three fuel tubes were manifolded together as were the three water cooling jacket tubes.



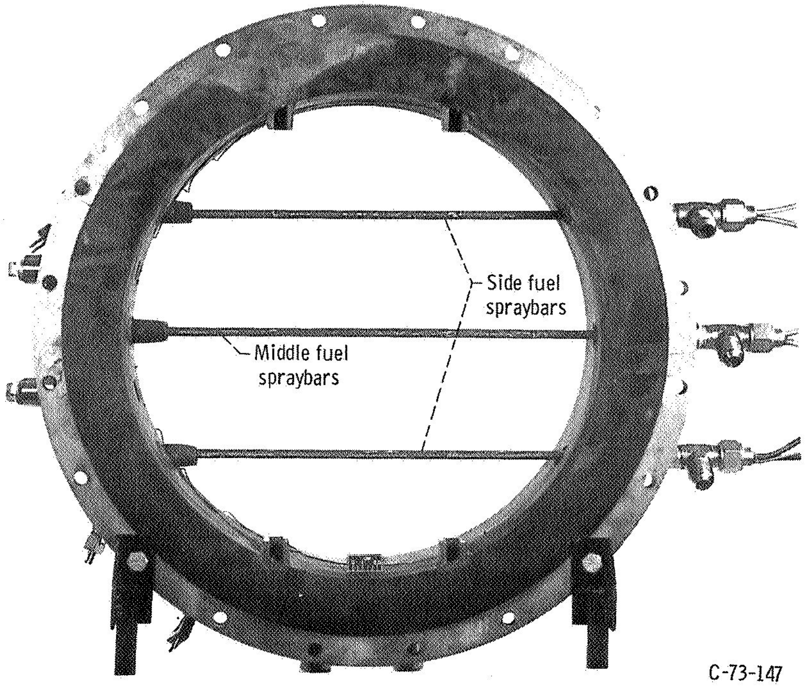
(a) Side spraybar. 0.95-Centimeter outside diameter tube with 0.16-centimeter-thick walls and 18 orifices (0.051 cm diam); spraybar length in stream, 41 centimeters.



(b) Middle spraybar. 0.95-Centimeters outside diameter tube with 0.16-centimeter-thick walls and 22 orifices (0.051 cm diam); spraybar length in stream, 49 centimeters.



(c) Cross section of spraybar.



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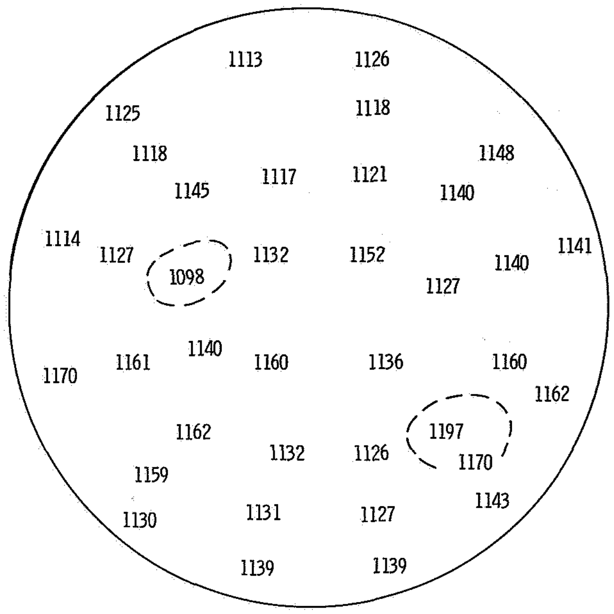
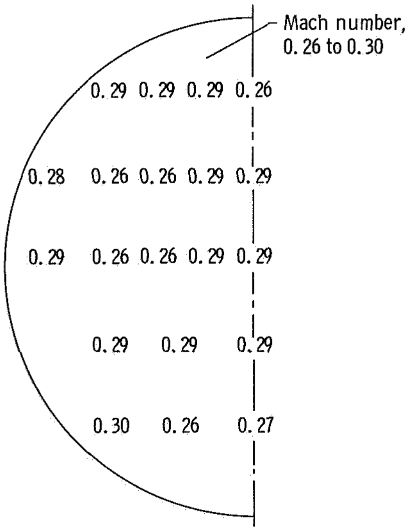
(d) View looking downstream.

Figure 3. - Fuel spraybars. Dimensions are in centimeters.



(a) Temperature pattern obtained at afterburner inlet thermocouple plane of figure 2. Afterburner inlet velocity, 150 meters per second; afterburner inlet static pressure, 1 atmosphere; preheater inlet temperature, 450 K; preheater fuel-air ratio, 0.0187. Dashed circles enclose temperature values that deviate by more than 30 K from the average temperature, 1140 K.



(b) Mach number profile obtained at fuel-injector plane of flameholder casing. Average Mach number computed from gas flow rate, 0.275; afterburner inlet velocity, 150 meters per second; inlet static pressure, 10 newtons per square centimeter; preheater inlet temperature, 450 K; preheater fuel-air ratio, 0.012; afterburner inlet temperature, 920 K.

Figure 4. - Typical afterburner inlet profiles for test hardware.

Relatively uniform inlet air velocity and temperature profiles were present at the combustor inlet. Figures 4(a) and (b) are typical inlet air temperature and Mach number profiles for this test facility.

CALCULATIONS

To include the effects of vitiation of the inlet air and incomplete combustion in the preheater, the afterburner fuel-air ratio (unburned) was computed by dividing the total fuel flow available to the afterburner by the available unburned airflow. All data are presented in terms of this fuel-air ratio.

The inlet velocity was calculated from the measured airflow rate, the inlet reference area of the afterburner test section, the average inlet total temperature, and the inlet static pressure.

The combustion efficiency was defined as the ratio of the heat released in the afterburner to the chemical energy of all fuel entering the afterburner. Heat-transfer losses from the duct components and the vitiating effect of the direct-fired preheater were included in the calculations. The combustion efficiency equation, its derivation, and an error analysis are given in reference 7.

The U.S. Customary Units system was used for primary measurements and calculations. Conversion to SI units (System International d'Unites) is done for reporting purposes only. In making the conversion, consideration is given to implied accuracy and may result in rounding off the values expressed in SI units.

TESTING PROCEDURE

To simulate typical 1240 K afterburner inlet air conditions the indirect fired preheater supplied the vitiating preheater with 460 K air. The vitiating preheater increased the afterburner inlet temperature to 1240 K with an operating fuel-air ratio of 0.0216.

A constant water flow of 0.1 kilogram per second at 290 K was supplied to each fuel spraybar jacket. The afterburner inlet total pressure was held constant at 10.4 newton per square centimeter and the inlet velocity at 152.5 meter per second. At this condition fuel was supplied to the spraybars to give a fuel-air ratio of 0.01. On completion of several successful spontaneous ignitions performance data were taken. No attempt was made to vary any of the parameters.

RESULTS AND DISCUSSION

The testing for this program was conducted in two brief phases, spontaneous ignition and performance. The test data for these tests are given in tables I and II, respectively.

Spontaneous Ignition Tests

At afterburner inlet conditions of 10.4 newton per square centimeter total pressure, 1240 K temperature, and 152.5 meter per second velocity, three consecutive spontaneous ignitions were obtained while fuel flow was being increased toward a fuel-air ratio of 0.01. All three ignitions were smooth.

Two Kulite pressure sensors were used to measure pressure fluctuations. Ignition was observed by noting an increase in combustor pressure and by visual observation using a borescope located downstream of the afterburner. As there were no unsuccessful ignitions, no more ignition attempts were deemed necessary following the three successful attempts.

The likelihood of spontaneous ignition increases with increasing inlet temperature and decreasing velocity and vitiation. The appendix describes spontaneous ignition experience at constant vitiation and variable afterburner inlet temperature. In addition to variations in inlet temperature, variations in vitiation and pressure are described in reference 6.

All these tests were conducted with an inlet temperature of 460 K ahead of the vitiating heater. These conditions result in the amount of vitiation that would occur at an approximate flight Mach number of 2.4 for an advanced turbojet engine. At a lower flight Mach number the amount of vitiation required to obtain an afterburner inlet temperature of 1240 K would be increased, or conversely if the amount of vitiation were constant the afterburner inlet temperature would be decreased. In either case the likelihood of spontaneous ignition would be decreased.

Performance Evaluation

The performance tests were made at afterburner inlet conditions of 11.1 newton per square centimeter total pressure, 1240 K temperature, and 142.5 meter per second velocity. The fuel-air ratio was held constant at approximately 0.01 (0.0094 to 0.0099). This operating condition was held for 1 hour with no sign of unstable burning or durability problems. The measured combustion efficiency varied from 107 to 110 percent. This is thought to be 100 percent when the measurement errors described in reference 7 are considered. The calorimetric determination of combustion efficiency is relatively inaccurate with low temperature rises such as were present for these tests.

Effects of increased fuel flow. - No tests were made to determine the sensitivity of this afterburner configuration to an increase in fuel-air ratio. It is thought, however, that increasing the fuel-air ratio will decrease combustion efficiency until a blowout eventually occurs. Increasing the number of spraybars should extend the fuel-air ratio range over which 100-percent combustion efficiency can be expected.

Spraybar configuration in an afterburner without V-gutters. - Although only one spraybar configuration was tested, spraybar arrangement (concentric rings, parallel bars or whatever) is probably unimportant for this type of afterburner, provided the bars are spaced far enough apart to prevent interference of adjacent flame zones. Also, the spraybars should be oriented so as to spray the bulk of the fuel perpendicular to the normal airflow; however, sufficient fuel should enter the recirculating wake of the spraybar so that stable flame seating occurs.

Spraybar cooling jacket. - Inconel and copper were both used as water jacket materials for cooling the fuel spraybars. Both materials performed satisfactorily. The internal spraybar fuel temperature thermocouples read 430, 481, and 464 K for the side Inconel, middle Inconel, and side copper-jacketed spraybar, respectively, (fig. 3) when operating without fuel at a 1240 K inlet temperature. With fuel flowing, these temperatures dropped to 300, 350, and 385 K respectively. The jacket water exit temperature was about 30 K higher than the inlet temperature on the short spraybars and 33 K higher on the long spraybar.

Insulating the fuel spraybars would further reduce fuel temperatures. At low fuel manifold temperatures it is unlikely that fuel plugging will occur as is common with uncooled spraybars operating at low fuel flow rates (refs. 1 and 3).

For these tests, 36 600 to 39 100 watts were extracted by the cooling water. This heat loss reduces the average air bulk temperature about 4 K. However, in the spraybar wakes, where the ignition probably takes place, the gas temperature reduction would be greater, and it could affect spontaneous ignition. The cooling water energy loss could be reduced by insulating the spraybars, thus reducing the amount of cooling flow required to prevent fuel coking. Also, the inlet temperature required for spontaneous ignition should be somewhat lower with insulated spraybars as less heat energy is removed from the air stream by the spraybar cooling fluid. The heat sink temperature for the cooling fluid must also be considered on a high speed aircraft mission.

SUMMARY OF RESULTS

A brief testing program was undertaken to determine if spontaneous ignition and stable combustion could be obtained in a jet engine afterburner operating with a vitiated inlet temperature of 1240 K and a pressure of 10.4 newton per square centimeter with ASTM Jet-A fuel. For these tests, simple water-jacketed spraybars were used. The fuel-air ratio was held constant at 0.01. The following results were obtained:

1. Smooth and repeatable ignitions were obtained.
2. Stable combustion at 100-percent combustion efficiency was obtained.
3. One hour of combustion time was accumulated without any sign of afterburner degradation.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio,
501-24.

APPENDIX - SELECTED GENERAL ELECTRIC GE-4 ENGINE AFTERBURNER DATA

The information presented in this appendix is from references 2, 3, and 4. Since these references are both classified and proprietary, they may not be readily available. Through permission of the General Electric Company and the Department of Transportation excerpts of these reports covering the subjects of spontaneous ignition and coking and spraybar durability are reproduced herein.

SPONTANEOUS IGNITION (REF. 2)

Flameholder Burning

Description - Flameholder burning on engine 006 was reported in the 4th Quarter Progress Report of 1969. During a run to max reheat, the number one flameholder ring was burned at eight locations on its outer perimeter directly behind a fuel orifice of the T-bar, and in the wake of a bulky quiet fix damper. Flameholder burning had not occurred on three max reheat tests on engine 004 with the same five tube, high-penetration spraybar and bulky spraybar damper. (See Figure 18A). A study of aerothermal conditions at max reheat revealed the following:

Engine	Outer Flameholder Lip Velocity, fps	Augmentor Inlet Mach No. $M_{5.1}$	Augmentor Inlet Pressure $P_{T5.1}$, psia	Outer Flameholder Temperature °F
004	693	.481	39.5	1645
006	607	.421	58.8	1635

The significance of these data was as follows:

- The burning occurred at high augmentor fuel flows.
- The pressure level was 50% higher on engine 006 than on engine 004.
- The flameholder lip velocity was 12% lower on engine 006 than on engine 004.
- The higher pressure level and lower lip velocity on engine 006 favored auto-ignition in the spraybar wakes.

The cause of flameholder burning was theorized to be that the bulky quiet fix damper and five tubes produced a wake behind the spraybar. Some of the fuel from the top inside orifice of the T-bar, and from the through orifice in the center fill tube, sprayed into the spraybar wake. The captured fuel recirculated into the wakes and ignited upstream of the flameholder at the high pressure and low velocity conditions. The flame upstream of the flameholder acted like a cutting torch and burned the flameholder lips. The eight burns probably coincided with spraybars located in the hottest streaks, in combination with the lower than average fuel penetration.

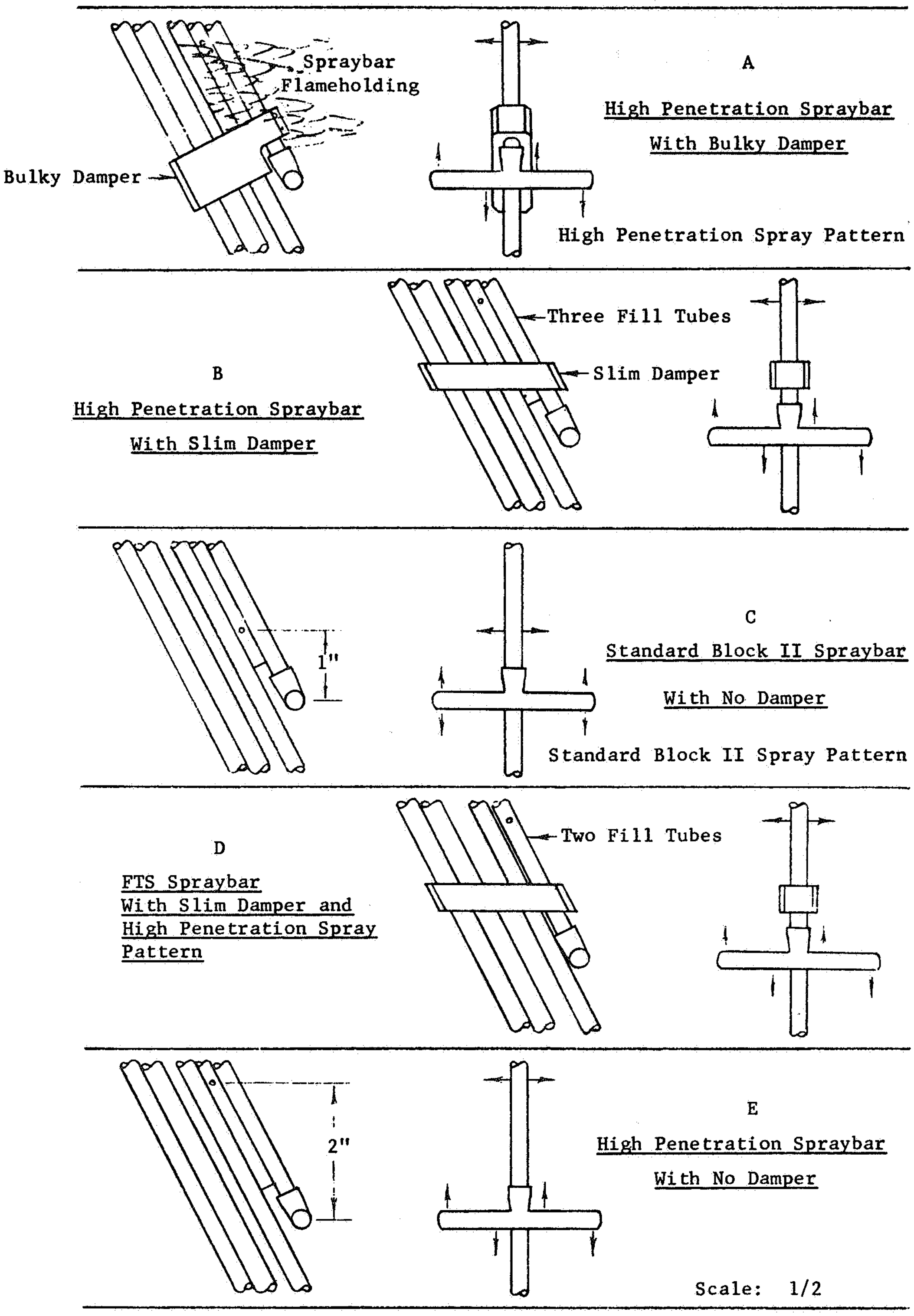


Figure 18 Five Spraybar Configurations Evaluated for Flameholding Characteristics

Flametunnel testing was carried out this quarter to determine the flameholding characteristics of spraybar configurations relative to their potential for burning the flameholder lips. These configurations included:

- Block II five tube high-penetration spraybars with:

Bulky Quiet Fix Damper	Figure 18A
Slim Damper	Figure 18B
No Damper	Figure 18E

- Standard Block II five tube spraybars (Figure 18C) without dampers, the center fill tube orifice 1" from the T-bar, and non-staggered T-bar orifices near the T-bar tips, which has never caused flameholder burning on an engine. (All other spraybars have center fill tube orifices 2" from the T-bar.)

- FTS four tube spraybar with a slim damper and high penetration T-bar (Figure 18D).

Determination of $T_{5.1}$ temperature levels at which spraybar flameholding occurred for the configuration of Figure 18A and 18C provides a measure of the flameholder burning problem observed on engine 006 versus the non-burning standard Block II spraybar configuration.

Results - The $T_{5.1}$ temperature levels for flickering and continuous spraybar flameholding taken during flametunnel testing are plotted in Figure 19.

Significant results are as follows:

- Spraybar flameholding occurred at engine 006 lip velocity, but not at engine 004 lip velocity with the high penetration spraybar and bulky damper (Figure 19A).

- Each spraybar configuration tested at 25° simulated swirl provides the following temperature margin over the high penetration spraybar with the bulky damper:

		Temperature Margin, °F	
Spraybar	Damper	Flickers	Continuous
High Penetration	Slim	40	40
Standard Block II	None	150	190
FTS	Slim	160	160
High Penetration	None	45	55

Discussion of Results - The flametunnel used for ignition testing was modified to hold one spraybar, as shown in Figure 20. The spraybar was mounted on a plate and could be swiveled to simulate turbine exit swirl angles of 10° to 25°. The flameholder was mounted at 15° to the free stream to simulate the effects of swirl at that angle. Only the outer fill system, consisting of a T-bar with four orifices and the center fill tube with a through orifice, was in operation since this was the part of the system responsible for number one gutter burning, and only this portion would fit into the 8" tunnel. Flameholding characteristics of each spraybar configuration were observed through a flametunnel window opposite the flameholder.

The majority of testing was carried out at an angle of 25° which represented severe level of swirl at the number one gutter immersion, and equivalent engine augmentor fuel/air ratio of

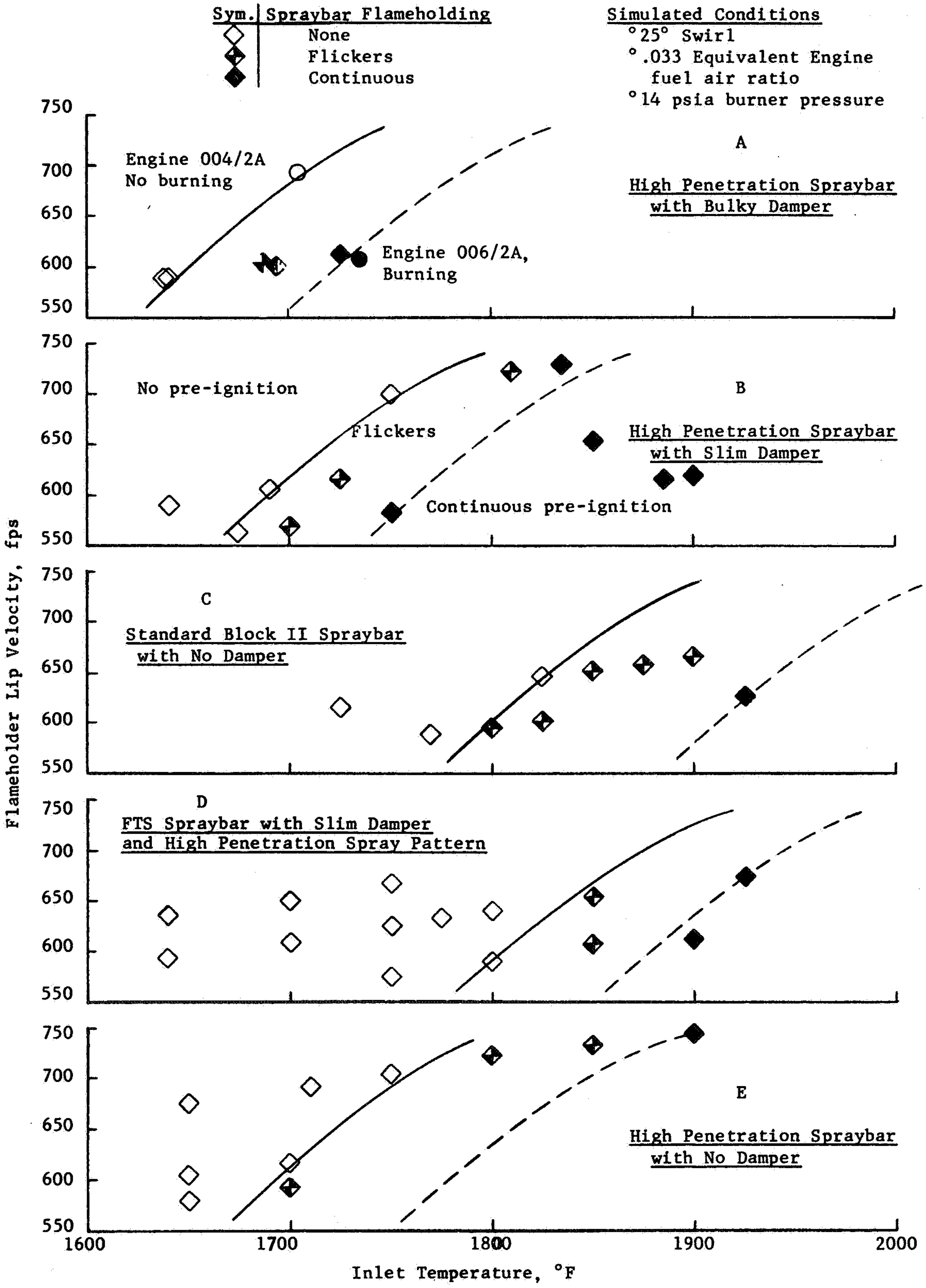


Figure 19 Flameholding Characteristics of Five Spraybar Configurations

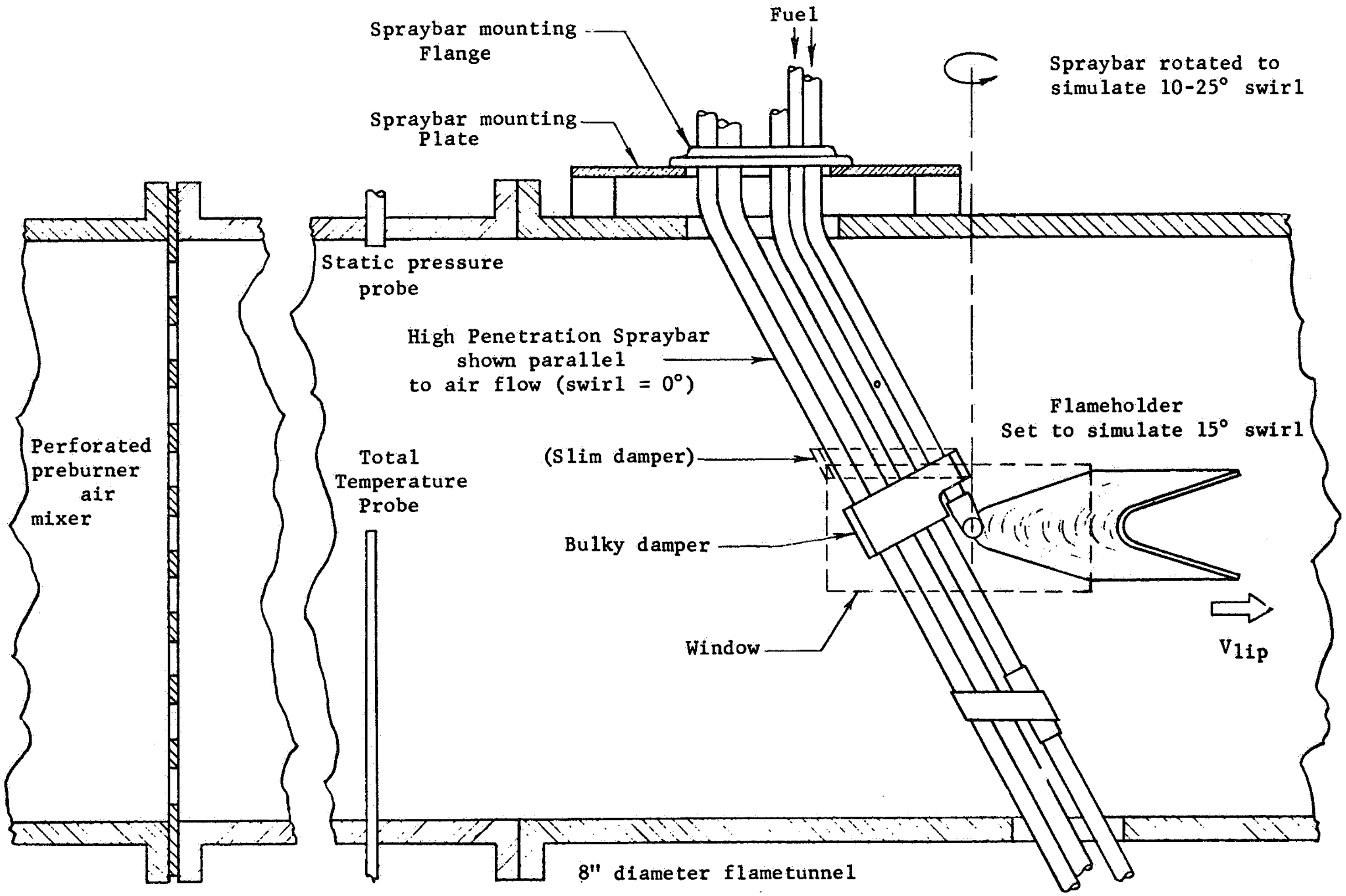


Figure 20 Flametunnel Configuration for Flameholder Burning Investigation

0.033. Pressure was limited to approximately 14 psi in the flametunnel, and engine lip velocities were simulated by adjusting air flow. Inlet temperature was varied to determine the effect of local $T_{5.1}$ profile on spraybar flameholding. Results are summarized in Figure 19.

Flameholder burning did not occur in the flametunnel. However, spraybar flameholding was observed between the T-bar and through hold in the center fill tube as either flickering or continuous flameholding depending on the inlet temperature level and lip velocity. Although flameholder burning did not occur in the flametunnel, it is theorized with the higher engine pressure, and hot streaks, the flameholding would develop into gutter burning. For purposes of comparison, the local $T_{5.1}$ temperatures from engine 004 and 006 were adjusted upward when plotted in Figure 19A by an amount equivalent to the engine-to-flametunnel pressure difference.

Conclusions

- The slim damper provided 40°F $T_{5.1}$ margin over the bulky damper on the five tube high-penetration spraybar. Removing the damper provided 45°F of margin.

- The standard Block II spraybar with the T-bar fuel injected well out from the region of flameholding provided sufficient $T_{5.1}$ margin against spraybar flameholding and gutter burning, in spite of the wake caused by five tubes and the center fill tube fuel injecting only one inch from the T-bar.

- The FTS spraybar with high penetration spray pattern and slim damper showed essentially the same magnitude of $T_{5.1}$ for flameholding as the standard Block II spraybar without a damper at the T-bar. This was presumably due to less effective blockage and/or wake from the two pair of spaced tubes in the FTS spraybar design. Flameholder burning is not expected with the FTS spraybar because its characteristics are equal to those of the standard Block II spraybar compared to the configuration that caused gutter burning.

SPRAYBAR COKING AND DURABILITY (REF. 3)

TUBE COKING TEST

Testing has continued on several component spraybar tubes to evaluate their potential margin of resistance to fuel coking. The tests were conducted in a simulated engine gas stream environment with varying peak gas stream temperatures. Three double tube configurations and one single tube design were tested until complete tube blockage by carbon shut off the flow. The tests were conducted by setting a peak gas stream temperature and cycling ambient temperature fuel into spraybars that had come to equilibrium. At a peak gas stream temperature of 2150°F (gas stream average temperature of 2060°F), tube plugging occurred during the first cycle for both the single and double geometry test specimens. The number of fuel on-off cycles to plug a tube increased as the gas temperature level decreased as shown in Figure 28. Plotted on this curve for baseline reference are the profile average temperatures for Block II engines 005, 006, and 007. Conclusions were as follows:

- At the conditions tested, the double tube geometry did not increase the temperature at which instantaneous coking occurs. This is because both tubes are initially at the same temperature when fuel is supplied, and when steady state conditions are reached the coking has already occurred.

- For the FTS program the spraybars have adequate margin against tube plugging from coking.

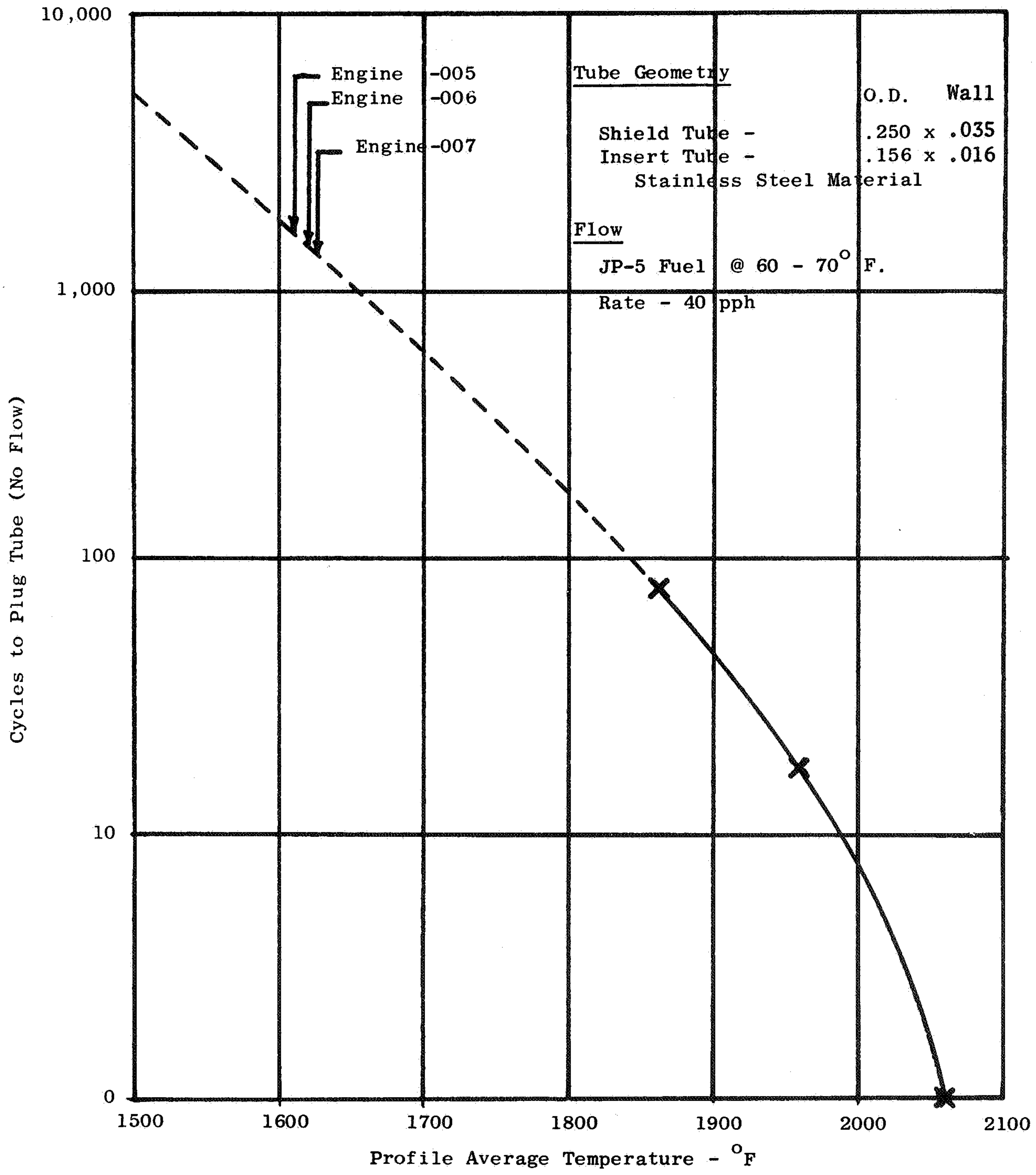


Figure 28. Spraybar Tube Coking Test Results. Cycles To Plug Vs. Average Profile Temperature

COMPONENT TESTING (REF. 4)

Several aspects of spraybar durability were investigated this quarter. The tests were made with single tubes in a small scale component flametunnel that simulated GE4 augmentor spraybar environment. A brief description of each test with the corresponding results follows:

- Alloy Effects on Coking

  The relative coking characteristics of L605, TD Nickel and TD Nichrome were evaluated. Single tubes of these materials, cycled side by side, showed that coke would build-up in the TD Nickel tube at approximately 5 times the rate of the L605 tube and 4 times the rate of the TD Nichrome tube. Earlier test experience with a completely uncoated TD Nickel spraybar had unexpectedly revealed massive sulfidation attack when operated with JP5 fuel. Even with coated tube segments no measurable improvement was observed during limited testing to date. Hence, the use of TD Nickel material for the spraybar was abandoned. TD Nichrome, though slightly more susceptable to coke build-up, is still sufficiently superior to L605 in durability, although not yet commercially available, to remain under evaluation for the production engine. The FTS spraybar will utilize L605 material.

- Low Flow Leakage Effects

  Component tests were conducted to evaluate tube coking susceptability from simulated small fuel system leakage into a spraybar during non reheat operation. These tests were run with flow rates from 1/2 to 10 PPH.

  It was observed that leaks in the range of from one to three PPH would result in solid coke deposits within two hours. Very low flows and flows in excess of three PPH did not cause short time coking. This series of tests showed the necessity of developing positive shut-off valving or providing other means to prevent fuel leakage from entering the fuel injector tubes. A fuel shut-off feature is being incorporated into the FTS spraybar design.

- Air Purge

  Air purging through the fuel tube was evaluated for preventing coke build-up during each augmentor operating cycle. One test series used a continuous air purge at all times when fuel was shut off. Another test series used an air purge for a five second interval immediately after fuel flow was terminated. The continuous purge was very effective in eliminating coke build-up. In fact, any coke present was completely cleaned out during the fuel-off cycle. The short air purge at fuel cutoff was also effective in retarding coke build up by reducing the residence time of residual fuel, but the short duration was not effective in removing any gum or coke film.

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TABLE I. - SPONTANEOUS IGNITION TEST POINTS

Test point	Total pressure, N/cm^2 abs	Total temperature, K	Airflow, kg/sec	Mach number	Velocity, m/sec	Fuel-air ratio (unburned)	Auto-ignition obtained
4212	10.2	1259	8.08	0.228	155.8	0	No try
4215	10.8	1237	8.13	.215	145.3	0.0103	Yes
4216	11.0	1241	8.13	.211	143.1	.0102	Yes
4217	10.7	1250	8.14	.211	143.5	.0101	Yes

TABLE II. - PERFORMANCE TEST POINTS

[Total temperature, 1241 K.]

Test point	Total pressure, N/cm^2 abs	Airflow, kg/sec	Mach number	Velocity, m/sec	Fuel-air ratio (unburned)	Combustion efficiency, percent
4222	11.1	8.15	0.211	143.0	0.0095	108.0
4223	↓	8.15	.210	142.5	.0095	107.2
4224	↓	8.14	↓	142.5	.0095	107.5
4225	↓	8.14	↓	142.5	.0094	110.0
4226	↓	8.14	↓	143.0	.0094	109.8
4227	↓	8.13	.209	142.0	.0099	108.4
4228	10.2	8.14	.230	156.0	0	-----

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