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Analytical Fuel Property Effects — Small Combustors

Phase II

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Final Report

By

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16. Abstract

A test program was conducted to study the effects of non-standard aviation fuels on a typical small gas turbine combustor, and to evaluate the effectiveness of design changes intended to counter the effects of these fuels. This study was a follow on to an earlier analytical study to predict the fuel effects and generate the design modifications evaluated in this program.

The T700/CT7 engine family was chosen for both studies as being representative of the class of aircraft power plants desired for this study. Fuel properties, as specified by NASA, are characterized by low hydrogen content and high aromatics levels. No. 2 diesel fuel was also evaluated in this program.

The tests demonstrated the anticipated higher than normal smoke output and flame radiation intensity with resulting increased metal temperatures on the baseline T700 combustor. Three new designs were evaluated using the non standard fuels. The three designs incorporated enhanced cooling features and smoke reduction features. All three designs, when burning the broad specification fuels, exhibited metal temperatures at or below the baseline combustor temperatures on JP-5. Smoke levels were acceptable but higher than predicted. This was partly due to the increase in baseline combustor smoke levels with the broad spec fuels being higher than anticipated.

One combustor of the three clearly demonstrated the best smoke and metal temperature characteristics. It was also easiest to manufacture and incorporate into a production design. GE with NASA's concurrence selected and subjected this combustor to a final component test program.

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SUMMARY

The T700/CT7 engine is a front drive turboshaft or turboprop engine (Figure 1) in the 1500-1800 shp (1120 -1340 kW) class as currently configured with high-power core flows of about 10 lb/sec (4.5 kg/sec). It employs a straight-through annular combustion system (Figure 3A) less than 5 in. (12.5 cm) in length utilizing a machined ring film cooled construction and twelve low-pressure air blast fuel injectors. Commercial and Naval versions employ two 0.5 Joule capacitive discharge surface gap ignitors.

The combustor employs a primary zone which responds to aromatics fractions carried in the fuel in terms of smoke and flame radiation. The primary zone was developed to provide a balanced trade-off between acceptable cold day ignition and non-visible smoke. In-as-much as smoke requirements are relatively relaxed for small diameter plumes, the primary zone stoichiometry for this application is richer than that found in larger engine applications.

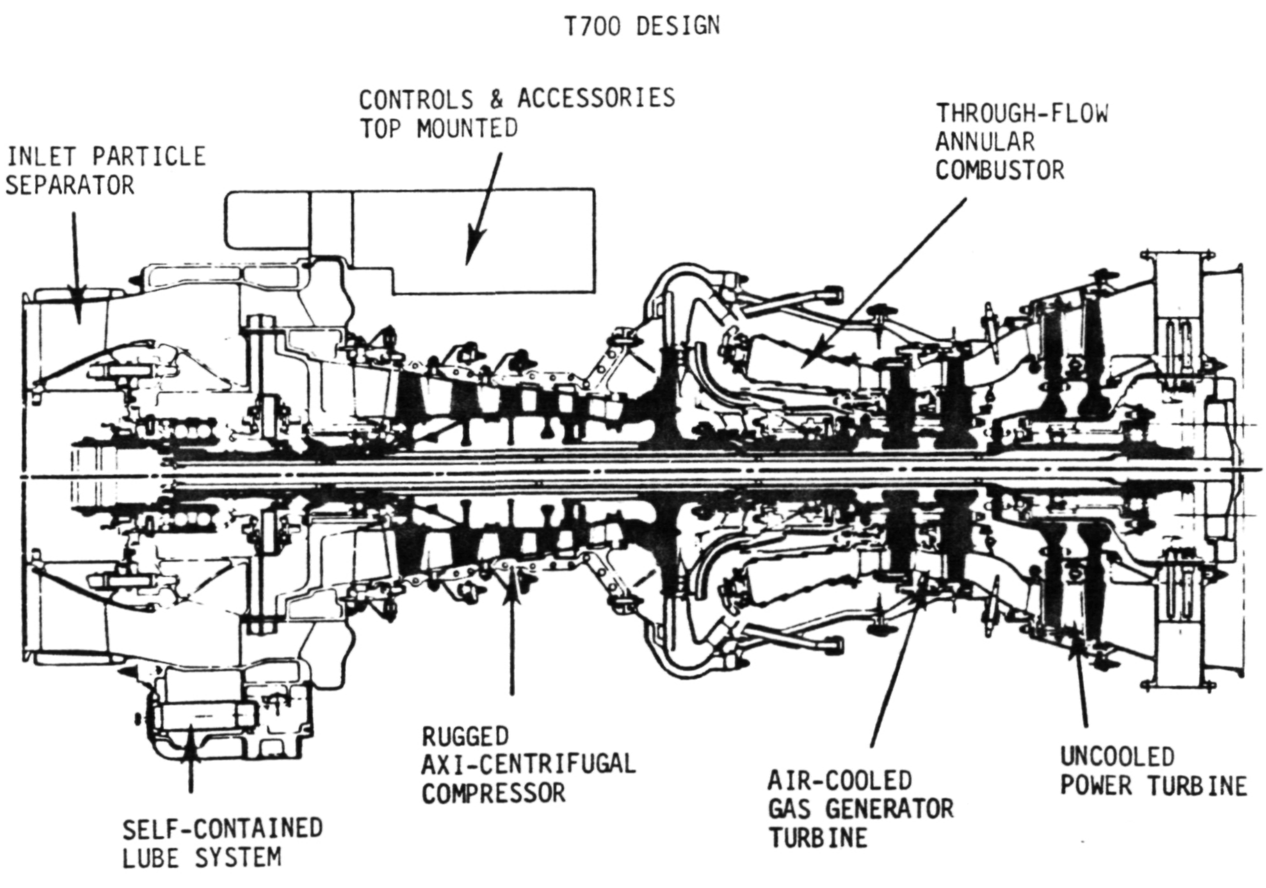


Figure 1. T700 Engine Cross Section

The three combustor concepts selected in Phase I were built and tested on JP-5, #2 Diesel, and the two NASA ERBS fuels (12.8, and 11.8). They were evaluated with respect to:

- *Smoke
- *Metal Temperatures
- *Profile and Pattern Factor Effects
- *Gaseous Emissions (Carbon Monoxide, Unburned Hydrocarbons, and Oxides of Nitrogen)
- *Complexity and Manufacturability

The DFIC Combustor was selected on the basis of superior test results to undergo final parametric evaluation including:

- *Profile and Pattern factor
- *Smoke
- *Metal Temperatures
- *Gaseous Emissions
- *Idle Efficiency
- *Overspeed Protection LBO Performance
- *Lightoff/LB0 Performance

The effort performed in Phase II of this program applies only to a T700/CT7 engine family type combustor functioning in the engine as defined and does not necessarily apply to other cycles or combustors of differing stoichiometry. The program was not extended to any of the fuel delivery accessories such as pumps or control systems, nor was there any investigation of potential systems problems which might arise as a consequence of abnormal properties such as density which might affect fuel schedules or aromatics content which might affect fuel system seals.

INTRODUCTION

Phase II of the Fuel Property Effects - Small Combustors program was carried out to evaluate the combustor designs recommended in Phase I by means of testing actual hardware.

The three combustor concepts recommended in Phase I were designed to offset the effects of low hydrogen, high aromatic fuels. Two effects were identified in Phase I as being major problems - excessive smoke and excessive metal temperatures.

Broad Specification Fuels

Table 1 shows the specifications of the three broad-spec fuels evaluated in this program. Two of the fuels are ERBS blends - ERBS 11.8 and ERBS Jet Fuel (12.8). ERBS 12.8 represents a likely jet fuel product from a synfuels process

TABLE 1
Broad Spec Fuel Properties

Specifications	ERBS 12.8	# 2 Diesel Saybolt	# 2 Diesel NASA	ERBS 11.8
Composition:				
Hydrogen, wt%	12.64	13.36	13.01	11.64
Aromatics, vol%	29.8	--		48%
Sulfur, Mercaptan, wt%	*0.003, max	33.4%		
Nitrogen, Total, wt%				
Napthalenes, vol%	*13, min	7.35%		22.95%
Hydrocarbon compositional analysis				
Volatility:				
Distillation Temperature, °F				
Initial boiling point	318	394		245
10 Percent	364	430		301
50 Percent	417	514		421
90 Percent	520	604		584
Final boiling point	598			614
Residue, percent				
Loss, percent				
Flashpoint, °F	126	162		104
Gravity, API (60°F)				
Gravity, Specific (60/60°F)	.8423	.8514		*.863 ± .002
Fluidity:				
Freezing point, °F	-50	-5 (Pour Pt.)		-45
Viscosity, @ -10°F, CS	6.58			14.34**
Viscosity, @ +80°F, CS	*2-3			*2-3
Combustion:				
Lower Heating Value, Btu/lb	18,160	18,311		17,870
Thermal Stability:				
JFTOT, breakpoint temperature, °F (TDR, 13 max; and p, 25 mm)	492		489	410 min[2]

*Proposed value, not actually tested

** Deviates from original spec

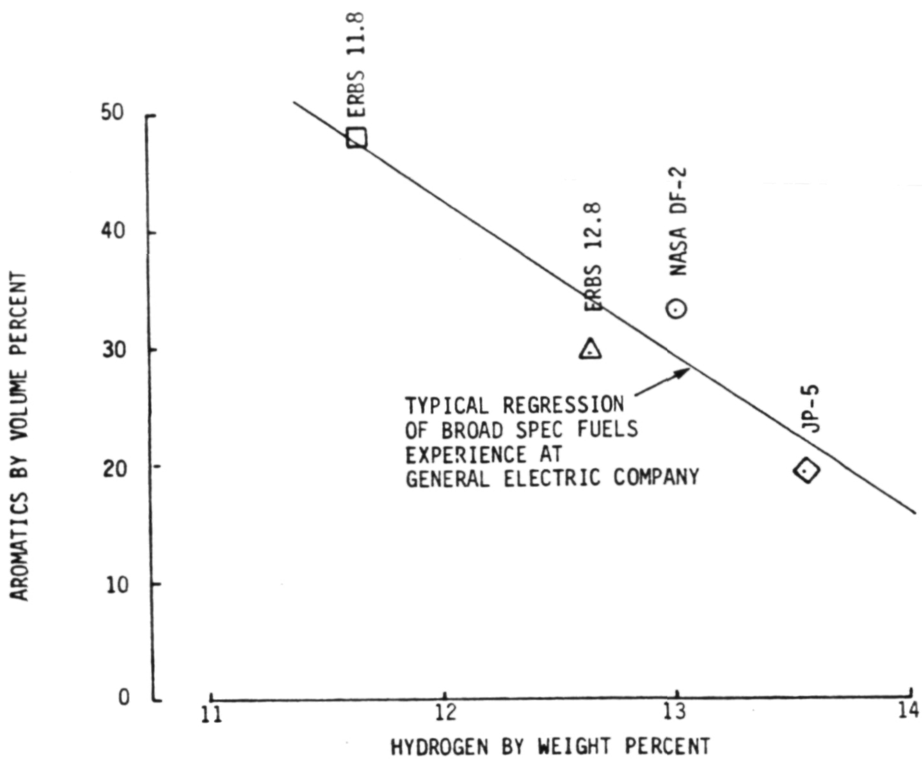


Figure 2. Fuel Aromatics vs Hydrogen Content

such as shale oil or solvent refined coal. ERBS 11.8 (11.8% hydrogen by weight) represents a worst case broad spec fuel. Number 2 Diesel was chosen for the third fuel for several reasons. One is that it represents a very likely real world substitute for JP5. The other is that it may show up secondary fuel effects from characteristics other than % hydrogen. These characteristics would be higher boiling range and lower thermal stability.

The ERBS fuels differ from common JP fuels and JET-A in that they have a very high aromatic content (up to 48% for ERBS 11.8) and therefore lower hydrogen. For common refinery-run fuels, hydrogen content correlates directly with % aromatics as shown in Figure 2. The ERBS fuels also have a higher density and a lower heating value per pound than JP5 or JET-A as well as a higher volatility and end point. The low hydrogen/high aromatics are known to produce high particle content in flames causing additional smoke and radiant luminosity or heat flux which creates abnormal increases in operating temperature of the combustor walls.

No. 2 Diesel has a slightly higher hydrogen content than the ERBS Jet Fuel but is still lower than JP5. Total aromatics are higher than ERBS 11.8, but naphthalenes are kept very low due to their adverse effect on Cetane Index. Naphthalenes have proven to have a more dramatic impact on smoke than monocyclic aromatics. Diesel fuel also has a higher boiling range, lower thermal stability, and higher viscosity than JP5 or JET-A. These properties may affect atomization quality and increase the tendency of the fuel to pyrolize before burning. This will also increase smoke and carbon deposition.

Motivation

The need for this type of program was created from the worldwide energy crisis that began in the early 1970s. High quality aircraft fuels have been traditionally derived from petroleum feed stocks. Limited and dwindling worldwide reserves of crude petroleum have driven prices up and has placed an upper limit on availability of certain distillates.

A number of approaches are available to relieve the problem in both the short and long term.

- o Conservation - The most immediate solution is to reduce fuel use. In the short run, fewer domestic flights and flying with higher load factors make better use of existing aviation fuel supplies. In the long run, introduction of growth and new engine designs which are more fuel efficient plus introduction of airframes with lower drag can make potentially vast improvements in both usage rates and cost per passenger mile.

  In parallel, it is possible to automate flight profiles for minimum fuel consumption through use of microprocessors.

- o Broadening of Aircraft Fuel Specifications - This is a way of increasing the yield of aircraft quality fuel from a given amount of feedstock. A number of programs have been underway for the last few years to determine the impact of wider fuel specifications on aircraft engines and their components, particularly the combustor.

  In general, it has been shown that, when using broad specification fuels, a potential exists for reduced combustor life, narrower starting envelopes, increases in smoke and gaseous pollutants, poor thermal stability, and a greater tendency to foul the fuel handling systems.

- o Derivation of Nonpetroleum Fuels - Fuel grade hydrocarbons can be derived from sources such as shale, tar sand, and coal which are available from huge deposits in North America. As these resources are exploited, broader fuel specifications may become necessary especially if the fuel is obtained from coal. The purpose of this program is to evaluate newer combustor designs in small engines to minimize or eliminate some of the problems of broadened fuel specification.

COMBUSTOR DESIGN DESCRIPTION

The baseline combustor for this program is the CT7 combustor used in Naval and commercial applications. A cross section of this combustor is shown in Figure 3A and a photograph is shown in Figure 3B. The combustor is a full annular machined ring design with demonstrated low smoke and 5000 life on JP5 or JET-A. Predicted smoke characteristics of the T700 combustor from Phase I analysis are shown in Figure 4. Phase I of this program predicted a 0.2:1 life ratio reduction on ERBS 11.8 and an increase in smoke number from 28 to 50. The objective of the new combustors is to achieve metal temperatures and smoke levels of the baseline combustor with JP5 on ERBS 11.8.

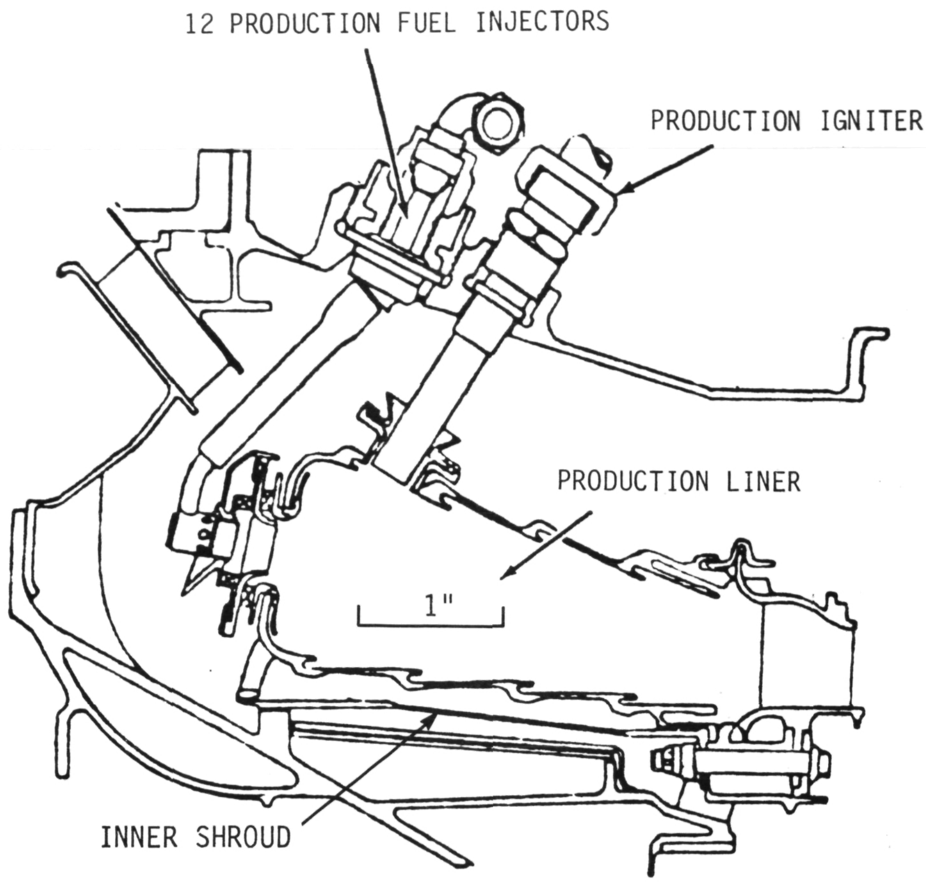


Figure 3A. Baseline T700 Primerless Combustor Cross Section

Figure 3B. Baseline Combustor With Thermocouples Installed

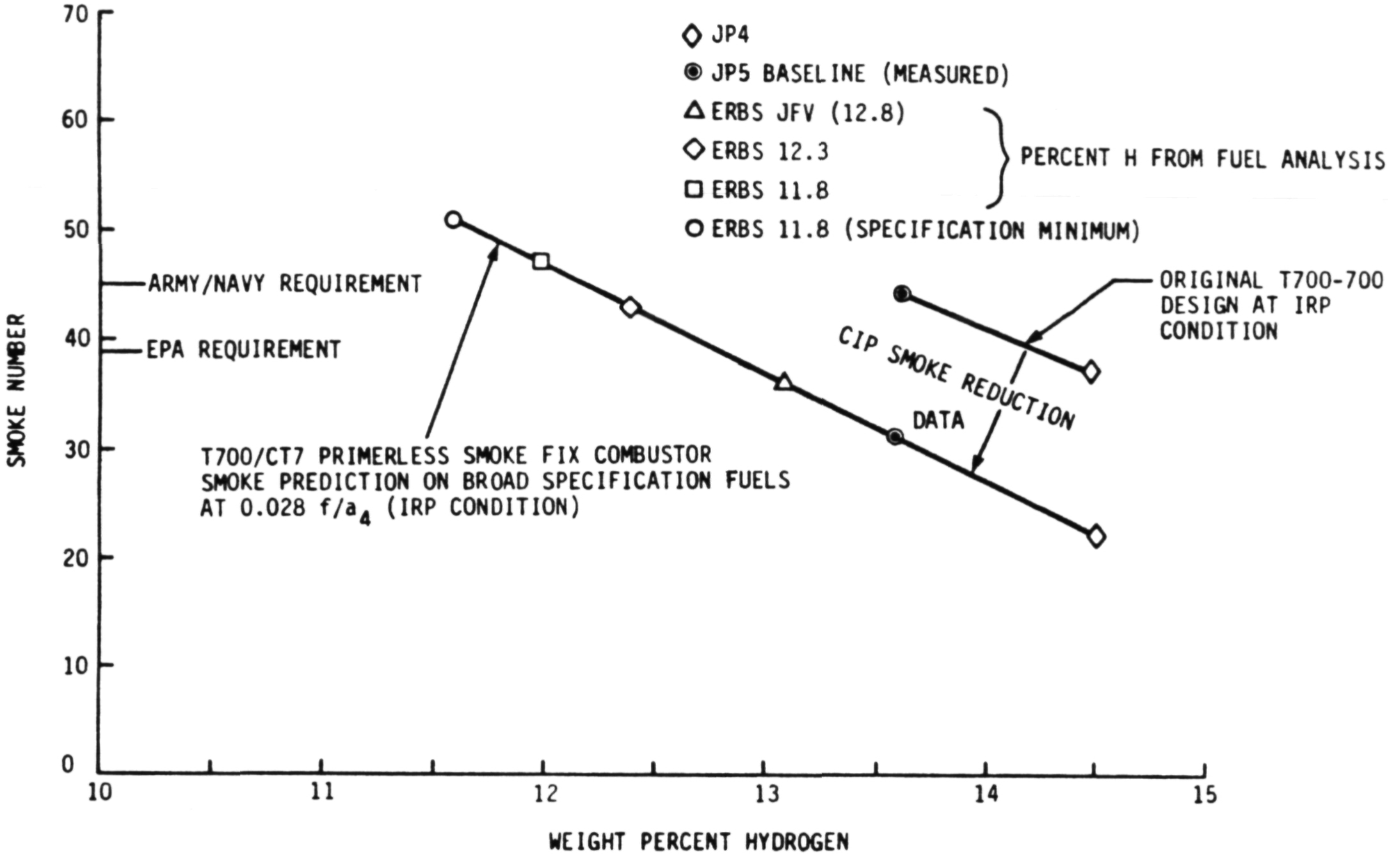


Figure 4. T700 Engine Smoke Characteristics Predicted In Phase I

The three new concepts evaluated include the following features:

- Advanced fuel injectors
- Advanced liner cooling techniques
- Combustor airflow redistribution
- Variable geometry swirlers
- Staged combustion (sector burning)

The Concept Approach Matrix (Table 2) shows the application of the features to the three concept combustors. Cross-sectional views and photographs of the three concepts are shown in Figures 5A&B, 6A&B, 7A&B and 8A&B.

Concept I Reverse Flow Convection Cooled Combustor (RFCC)

The RFCC combustor cross section is shown in Figure 5A. The combustor is built around a production T700 combustor incorporating sheet metal spinnings to form the convection flow paths.

The main spinnings which form the inner and outer convection jackets are welded to the combustor at one end and interlock between two seal strips at the other end to form a sliding joint, to relieve thermal expansion. The convection annulus is partitioned into individual convection circuits for each panel by means of spun sheet metal dams, which are welded to the combustor shell and slide against the convection jacket.

TABLE 2
New Concept Approach Matrix

New Concept #	Figure	Description	Advanced Fuel Injectors	Advanced Cooling Techniques	Airflow Redistribution	Variable Geometry	Staged Combustion
1	5A, 5B	Lean Dome (with sector burning if proven necessary) and reverse flow convection with impingement stage		X	X		X
2	6A, 6B 7A, 7B	Advanced airblast fuel injection combined with dilution flow/ impingement cooled shells	X	X	X		
3	8A, 8B	Simulated variable geometry swirler with impingement cooled replaceable shields		X	X	X	X

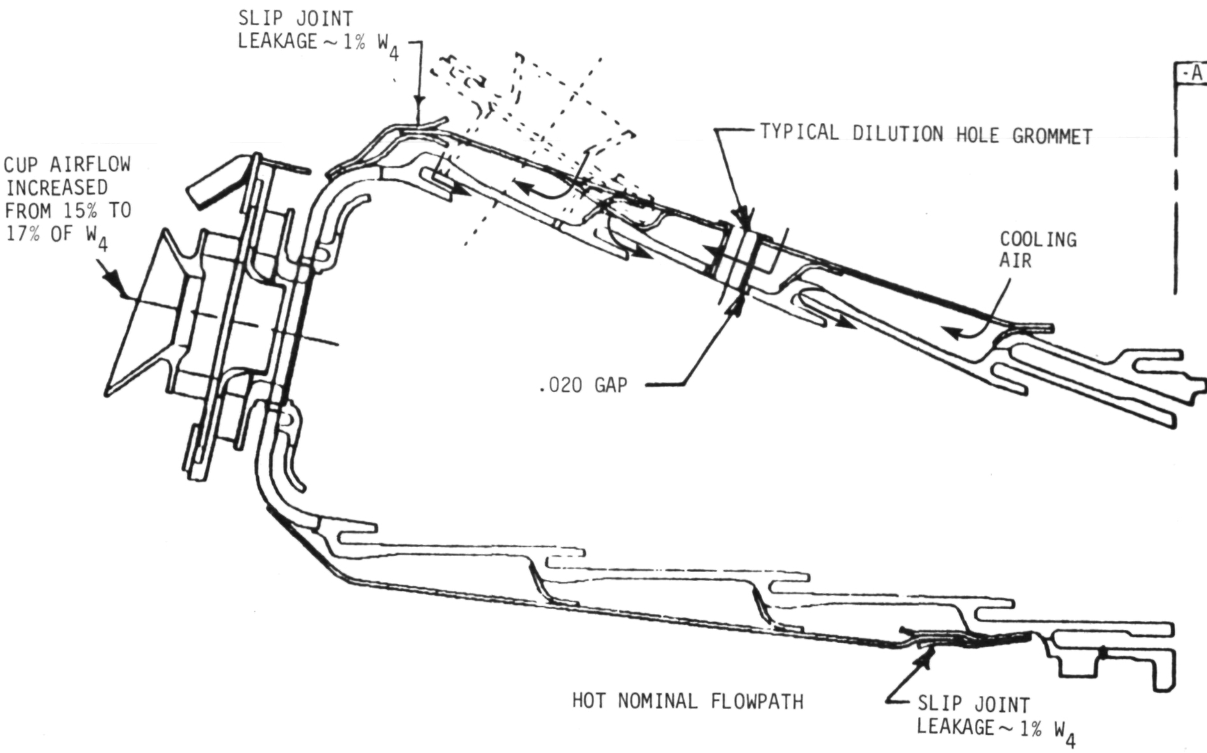


Figure 5A. Reverse Flow Convection Cooled Combustor Cross Section

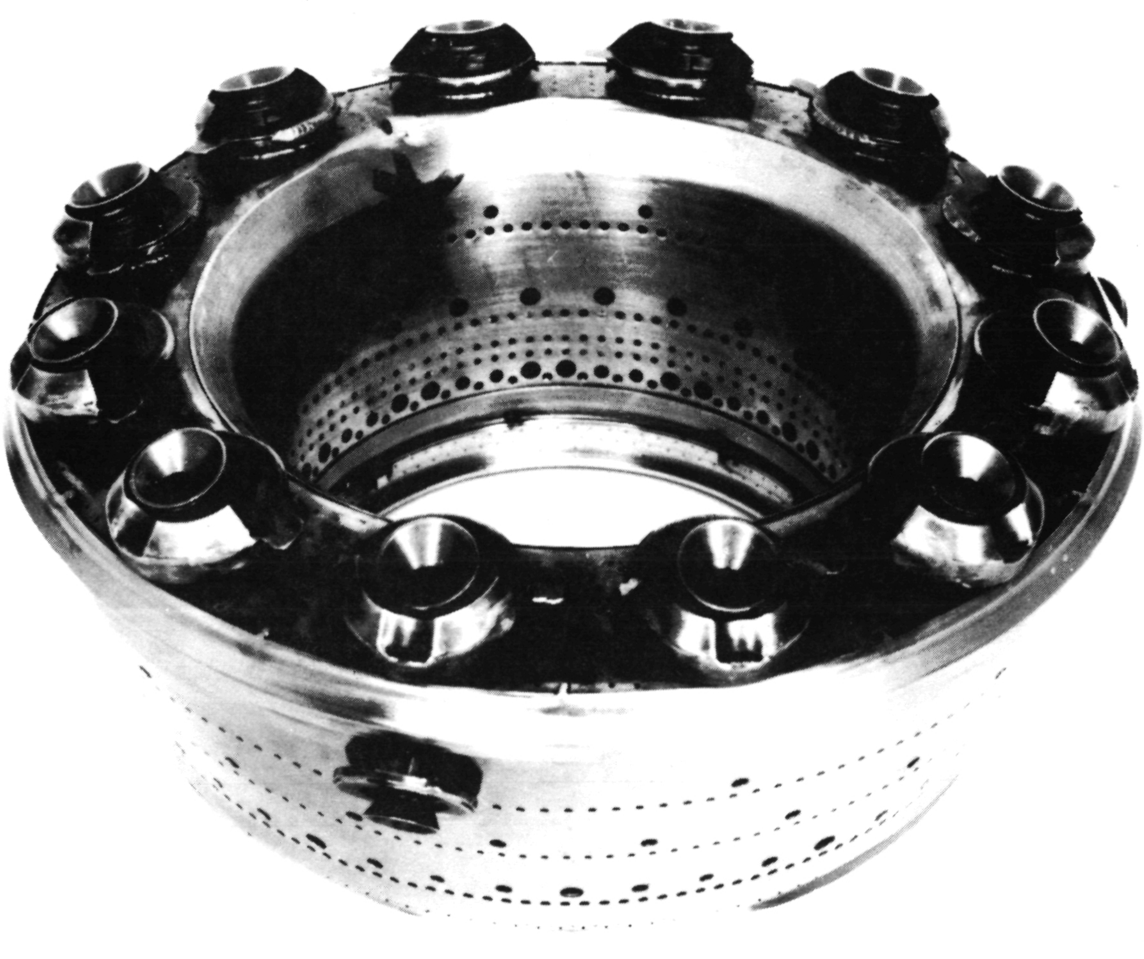


Figure 5B. Reverse Flow Convection Cooled Combustor (Thimbles Not Installed)

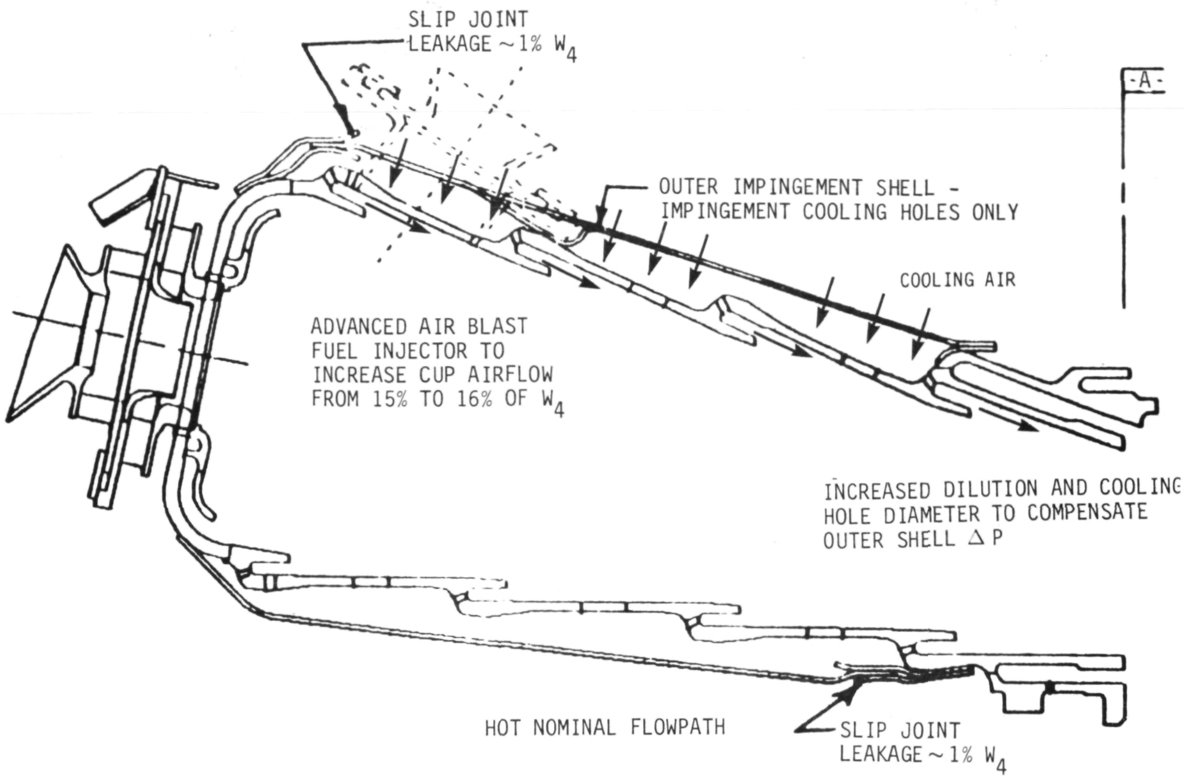


Figure 6A. Dilution Flow Impingement Cooled Combustor Cross Section

Figure 6B. Dilution Flow Impingement Cooled Combustor

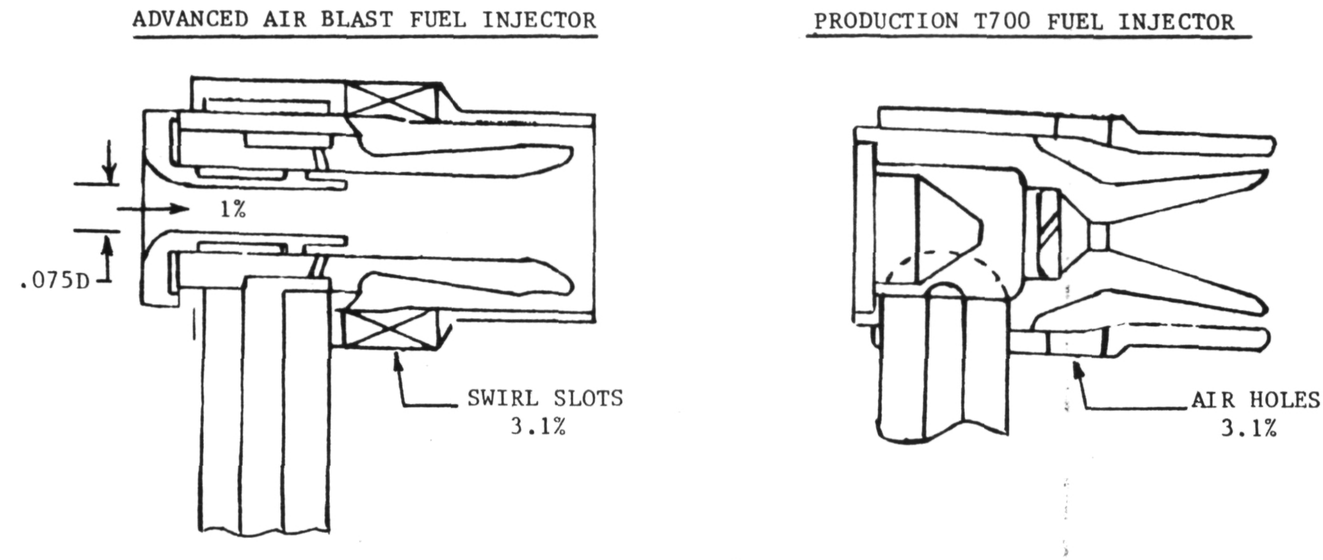


Figure 7A. Advanced Airblast and Production Fuel Injector Cross Sections

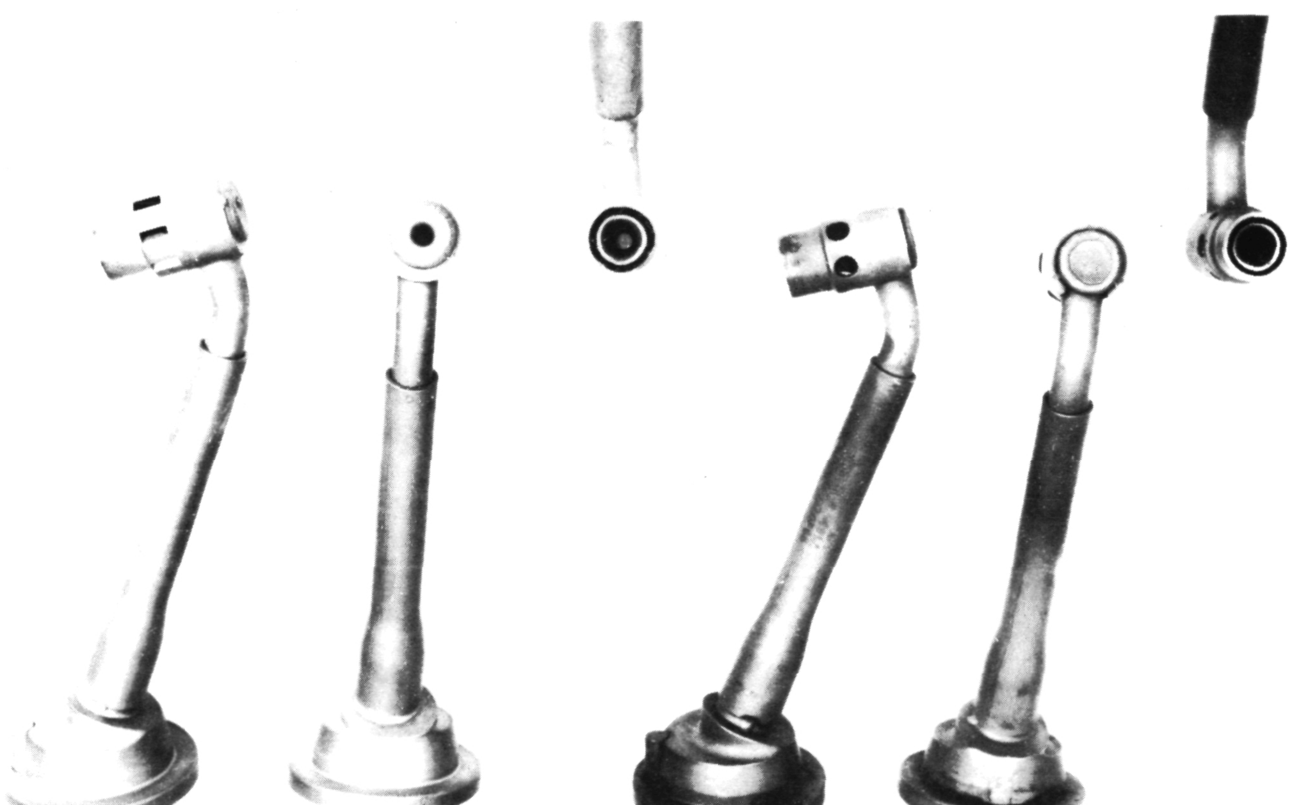


Figure 7B. Advanced Airblast Fuel Injectors and Production Fuel Injectors

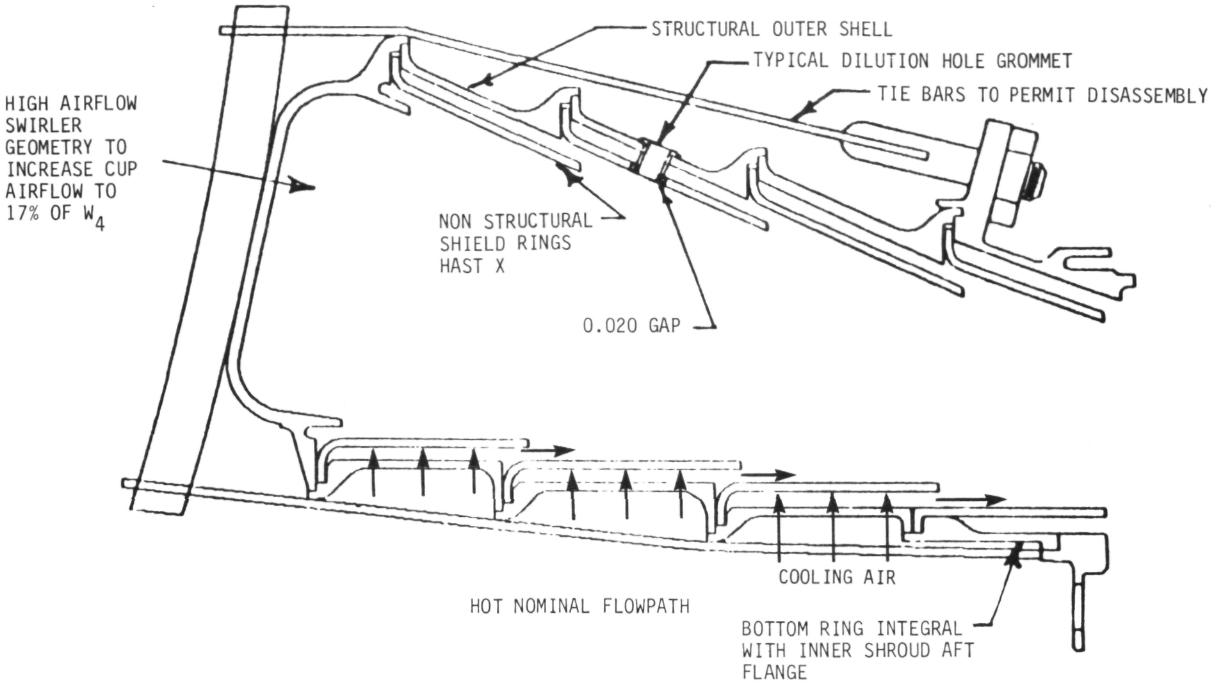


Figure 8A. Impingement Cooled Replaceable Shield Combustor Cross Section

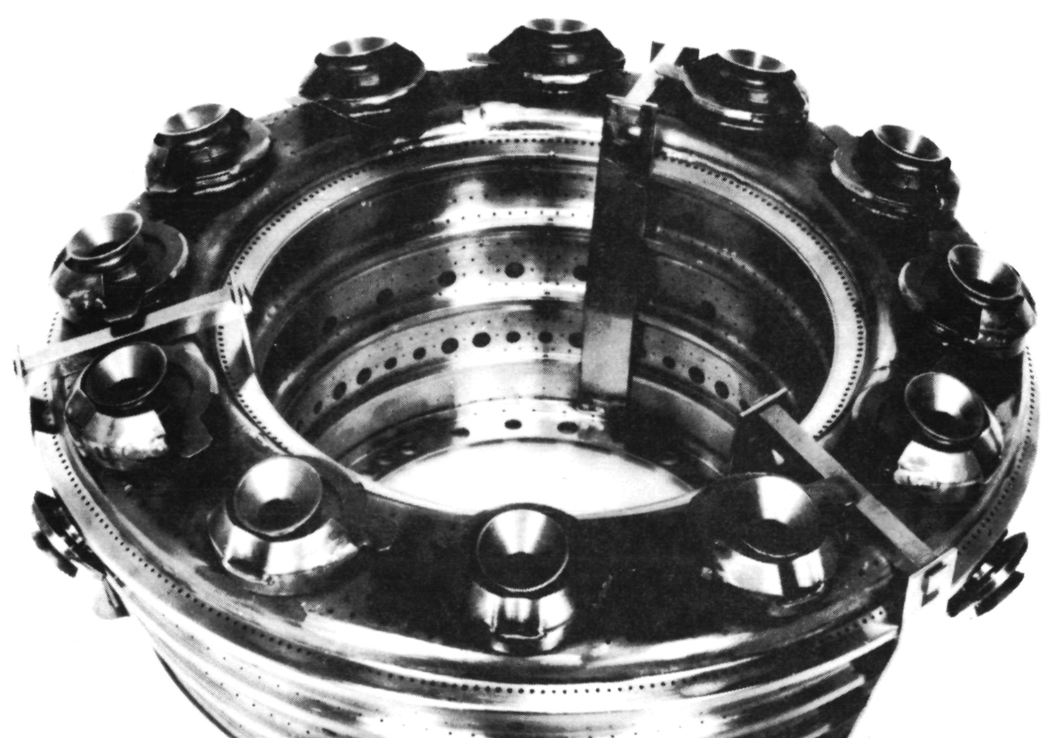


Figure 8B. Impingement Cooled Replaceable Shield Combustor

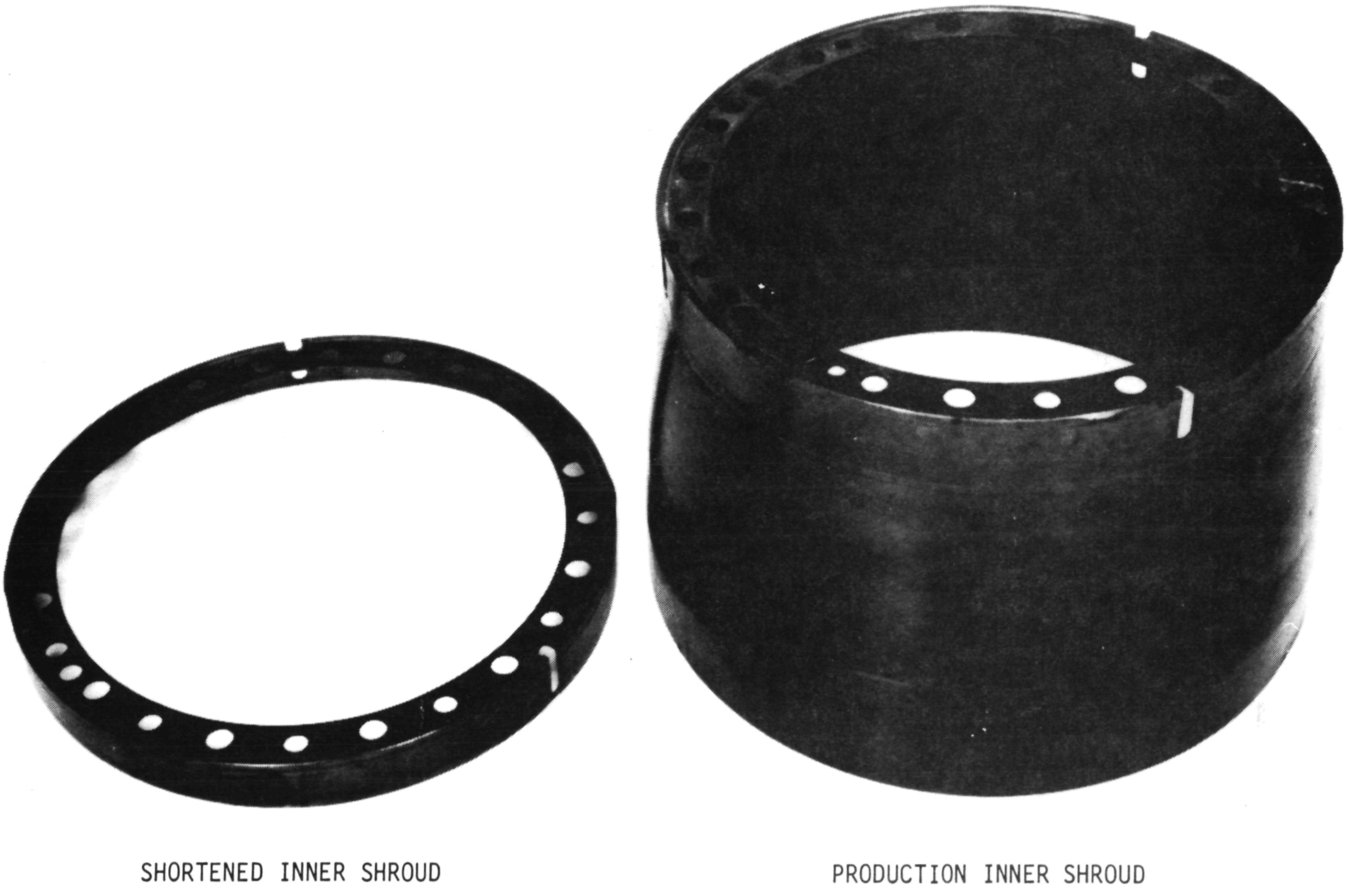
The attachment of the dams to the combustor shell requires that all except the first panel cooling holes be radial drilled instead of axial as on the production combustor.

Thimbles are used to carry dilution air through the convection annulus. The thimbles are welded to the jacket and extend through the combustor shell. It was necessary to limit diametral clearance between the dilution holes and thimbles to .010 because of trimming considerations. This made it necessary to line drill all dilution holes through the jackets and shell simultaneously. This line drilling procedure would probably not be considered feasible for production.

The jackets increase the envelope of the combustor. This was not a problem on the outer shell but it caused inadequate clearance with the inner flow path (fig. 3A). The inner flow path is a removable shroud which locates the combustor circumferentially. It also acts as a convection accelerator to help cool the inner shell, and it serves as a heat shield between the sump on the engine and the inner shell of the combustor.

The placing of the convection sheath around the combustor makes the latter two functions of the inner shroud redundant. Since only the aft flange of the inner shroud is needed to locate the combustor, a shortened inner shroud (Figure 9) was made. The new piece consisted only of the aft flange with sufficient axial material to ensure structural integrity.

The aero design presents no significant change from the original concept except for the deletion of the accelerators from the convection path. These were considered optional in the proposal and deleted as unnecessary.



SHORTENED INNER SHROUD   PRODUCTION INNER SHROUD

Figure 9. Comparison of Shortened Inner Shroud and Standard Inner Shroud

Thin shell steady state heat transfer analysis was repeated on all three designs because there were sufficient deviations from the original Phase I designs to warrant it. Table 3 shows the results of the analysis.

The lean dome was achieved by using high flowing secondary swirlers. This puts an additional 2% of WA4 into the primary zone for smoke reduction.

This combustor proved to be the most difficult to build and to trim. Tolerance control on the sheet metal spinnings proved to be a problem, which was aggravated by the use of air dams and thimbles. The need to line drill the thimble holes to minimize leakage would not be practical on a production design.

Concept 2 - Dilution Flow Impingement Cooled Combustor (DFIC)

The combustor cross section is shown in Figure 6A and a photograph is shown in Figure 6B. The combustor is built around a production T700 combustor. The impingement jackets are sheet metal spinnings. The spinnings are identical to those on the RFCC combustor except for different hole patterns. Also, there are no air dams or thimbles. The seal arrangement for the jackets incorporates the same sliding joint arrangement as the RFCC combustor, permitting thermal growth between the jacket and combustor shell.

The combustor as originally designed and analyzed treated each panel as a separate entity and isolated its impingement flow from the adjacent panels. This meant that the impingement air for a given panel fed only the cooling and dilution holes for that panel. This resulted in the first panel receiving the least amount of impingement cooling and the 3rd panel the most. This combustor did

TABLE 3
Predicted Maximum Metal Temperatures - Three Prototype Combustors
ERBS 11.8 vs Baseline Combustor on Jet A

	ERBS 11.8				Jet A
	RFCC End of Pancl	RFCC Mid Panel	DFIC	ICRS	Baseline T700
1st outer	1335	1300	1291	1631	1482
1st inner	1319	1232	1257	1550	1452
2nd outer	1400	1250	1275	1580	1447
2nd inner	1344	1250	1237	1560	1447
3rd outer	1109	1056	1137	1575	1457
3rd inner	1086	1089	1075	1410	1457

not totally overcome the fuel effects in the Phase I analysis for this reason. In the final design, there is a common plenum under the impingement jacket. This permits an equal number of impingement holes for all panels. Some of the first panel impingement air eventually goes through the shell at the 2nd and 3rd panels. All panels now have impingement flows per unit area that are uniform and provide high levels of cooling.

A thin shell steady state heat transfer analysis of the design was repeated, and shows that the combustor, on ERBS 11.8 will run 200°F cooler than the baseline combustor on Jet A. Results are tabulated in Table 3. The prediction was borne out in testing. (See table 6, page 31.)

A cross section of the Advanced Airblast Fuel Injector is shown in Figure 7A next to a cross section of a production T700 fuel injector. Photographs of the two designs are shown in Figure 7B.

The injector employs a central air passage to admit an extra 1% of WA4 into the primary zone, and swirl slots in the air shroud to maintain spray stability margins and to improve the spray pattern. Figure 10 shows the advanced airblast nozzle spray pattern overlaid on the production nozzle spray pattern.

The advanced nozzle produces a hollow spray with wider overall distribution of the fuel. This compares to a rich core on the production injector. The improved fuel distribution, combined with additional air are responsible for the lower smoke emissions with this nozzle.

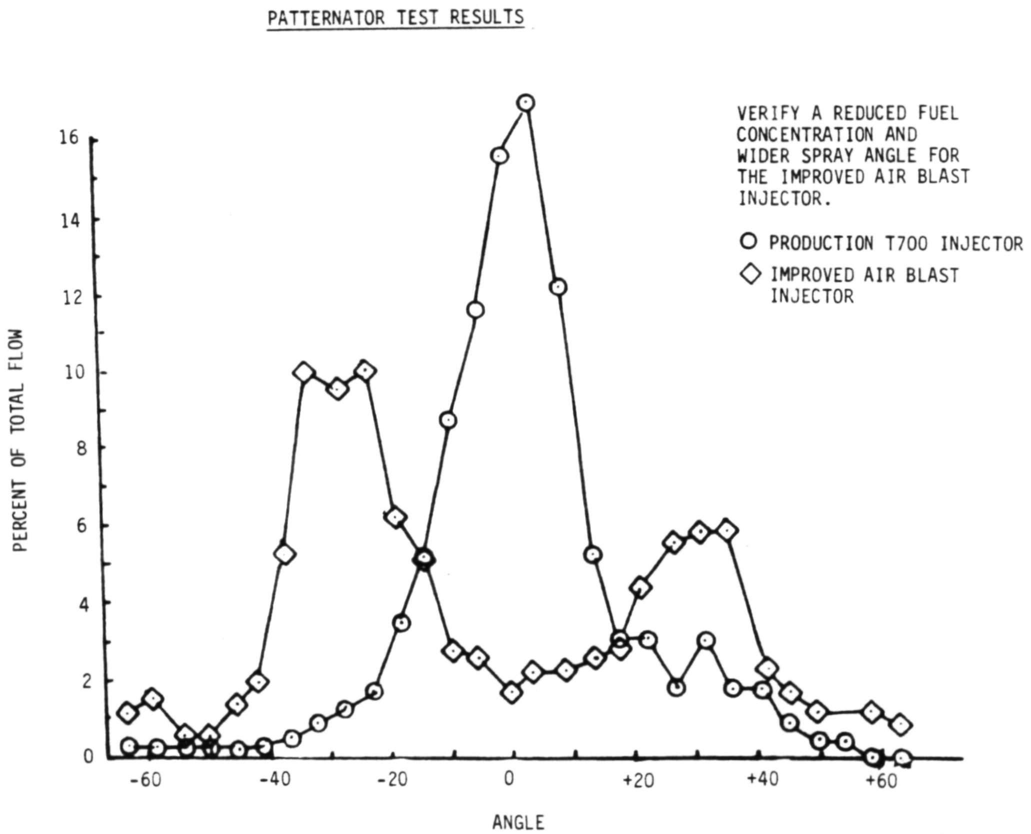


Figure 10. Patternator Results of Advanced Airblast Fuel Injector

Of the three combustor designs this one represents the least radical change from the production design. The same spinnings were used as for the RFCC combustor; and similar problems were experienced with tolerance control and fitup of the parts. The absence of thimbles and air dams made these problems far more manageable, however - to the point where this could be a production feasible design with a few modifications. The lack of thimbles is considered a major advantage as it eliminates a large number of small machined parts which could be misassembled.

Concept 3 - Impingement Cooled Replaceable Shield Combustor (ICRS)

A cross section of the ICRS combustor is shown in Figure 8A and a photograph is shown in Figure 8B. The ICRS combustor is a simplied version of the "shingled combustor." The principle is to isolate the structure of the combustor from direct contact with the flame. The combustor is made from a stack of structural shell rings with interlocking shield rings. The shield rings have no pressure drop across them and are allowed to float in the shell rings to relieve thermal stresses. The design permits replacement of the shield rings by disassembling the shell rings. To facilitate replacement, the rings are held together with straps and tackwelds rather than 360° welds as originally proposed. Thimbles are used to carry dilution air across the two rings and into the main combustor flow path.

The production internal flow path dimensions were not changed on this combustor. This means that the outside of the combustor exceeds the production combustor envelope. This required elimination of the inner shroud. The aft inner ring of the combustor serves the function of the aft flange of the production inner shroud. As with the other two designs, the double wall of the combustor makes the aerodynamic and heat shielding functions of the inner shroud redundant.

The original concept called for dilution flow impingment cooling of the shingles similar to concept 2. In practice, this proved a difficult concept to implement as it required a seal at the aft end of the shingles to regulate cooling air flow. Coming up with a practical design that could meter cooling air accurately and accommodate thermal growth of the singles proved impossible within the constraints of the program. The design was changed to just use the normal cooling airflow for impingement and to use thimbles for the dilution air. A thin shell steady state heat transfer analysis of the revised design showed that it would still produce acceptable temperatures. Results are tabulated in Table 3.

The production CT7 dilution trim was maintained on this combustor except that preferential cooling was not applied to the impingement cooled areas.

The large number of machined components makes this the most expensive of the three designs to produce; however, since all parts requiring close fitup are machined, tolerance control is not a problem. Once all of the parts were machined, this proved the easiest of the three combustors to assemble. The high cost is offset by the fact that damaged components can be replaced without replacing the whole combustor. This advantage is, however, mitigated by the fact that all three concepts are designed for a 5000 hour service life without repairs.

Another advantage of this design, which was not exploited in this program is that the shingles can be made out of ceramics or turbine bucket alloys as they are simple shapes and not load carrying members. This combustor would make a good vehicle for testing such materials in a future program.

COMPONENT TEST RESULTS AND DISCUSSION

Overview and Summary

The three prototype combustors and the baseline were tested in the T700 heavy duty test vehicle, a cross section of which is shown in Figure 11. Gaseous emissions were measured using the GEORGE gas analyzer console (Figure 12), which is set up to measure HC, CO, CO_2 and NO_X.

Two systems were used for measurement of smoke. One was the GE smoke cart (Figure 13) which uses the ARP1179 smoke spot method to measure smoke. The other method was by means of a weighed particulate sample taken through the system shown schematically in Figure 14. In the past, the weighed particulate technique has been the preferred method for component rig tests as the results are more consistent and correlate well with engine test data.

The three prototype combustors were tested on the three broad spec fuels. The baseline combustor was also tested on JP5, in addition to the other three fuels.

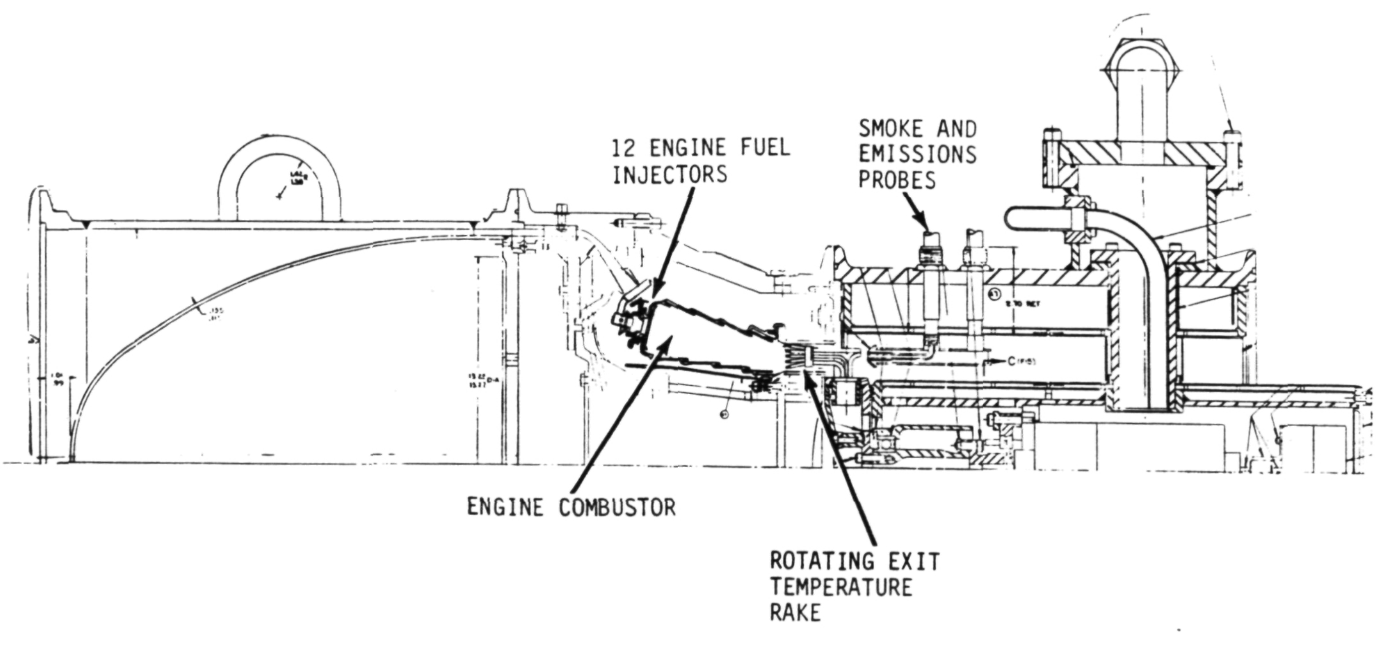


Figure 11. T700 Heavy Duty Test Rig

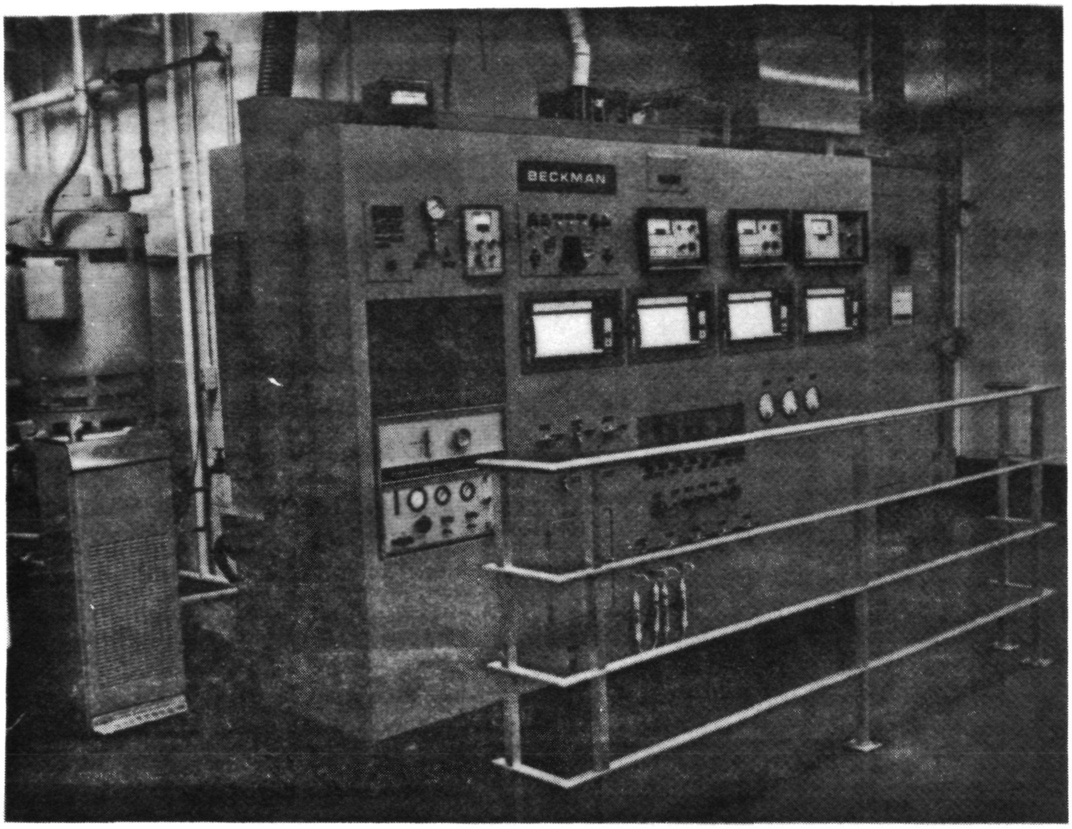


Figure 12. The "George" Gas Analysis System

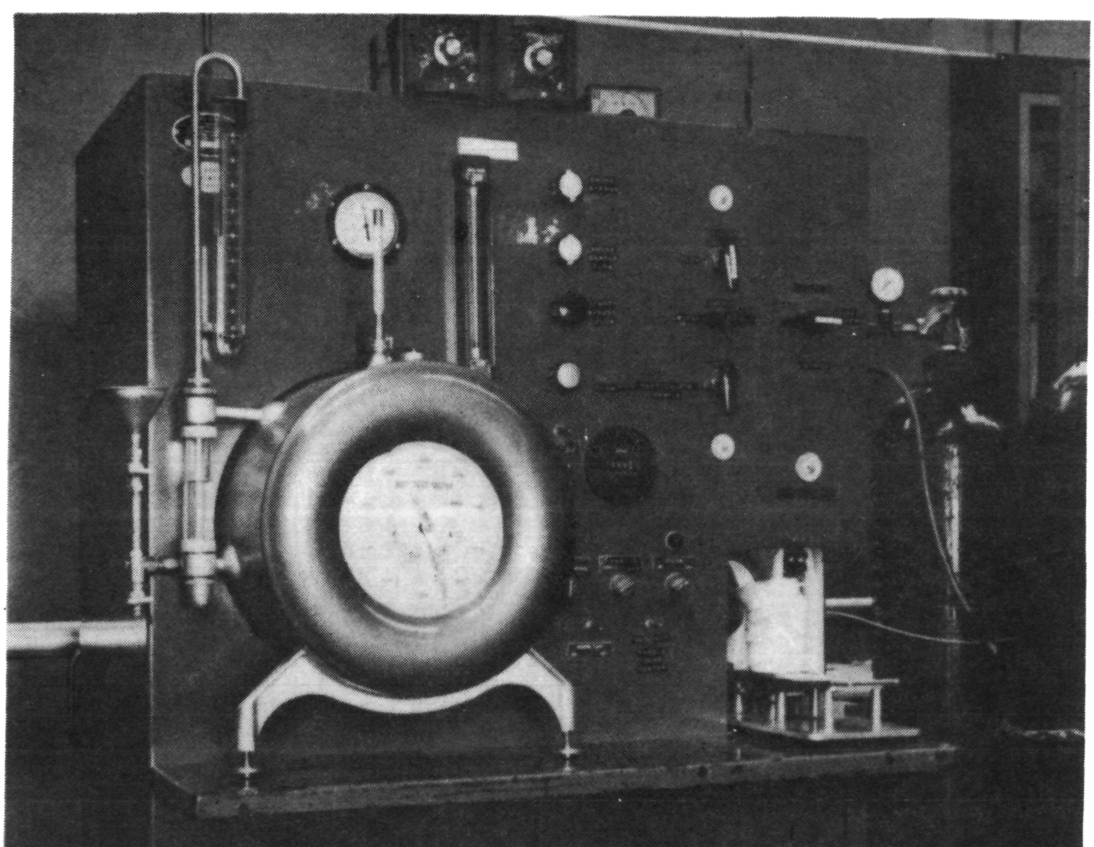


Figure 13. General Electric Smoke Cart

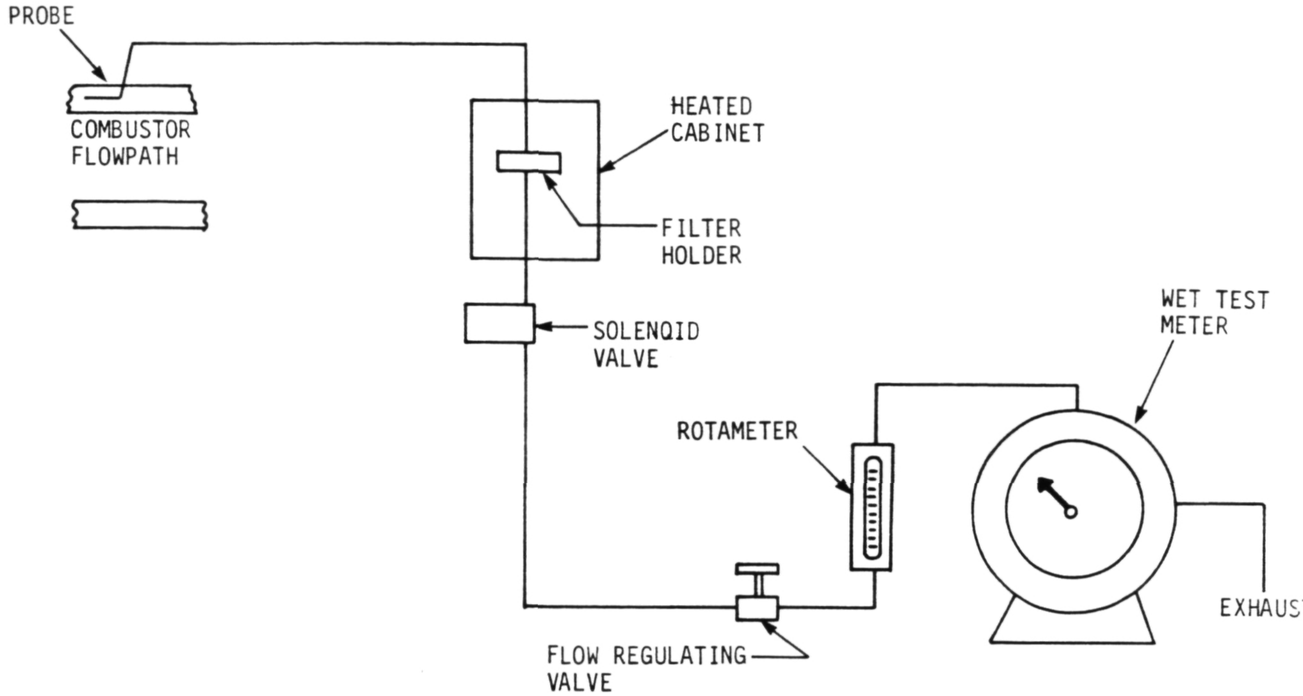


Figure 14. Schematic of Particulate Measurement System

Following the initial screening tests, the relative performance of the three combustors was evaluated to select the most promising design for final evaluation. A selection matrix was made (Table 4) and the DFIC combustor was shown to be the best overall design. This selection was made on the basis of the following criteria:

- o Metal temperature
- o Degree of smoke reduction
- o Difficulty to manufacture
- o Cost to manufacture
- o Likelihood of adoption on a production design

The comparison showed the Dilution Flow Impingement Cooled design to be the most advantageous as it gets the best results in all categories.

This cooling concept is also being used for the LV100 tank engine, a carbon slurry demonstrator combustor, and is being considered for a low emission CF34 combustor.

Final Parametric Evaluation studied the idle, lean stability, and lightoff performance, and repeated the smoke measurements. The DFIC combustor was low on pressure drop in the first phase of the testing (3.2% vs a design 3.85%) so it was reworked to the design ΔP for the final parametric phase of the testing.

TABLE 4
Relative Evaluations of Three New Concepts

Combustor	EKBS 11.8 Corrected Smoke #	Max. Metal Temp	Difficulty To Manufacture	Cost to Manufacture	Likelihood of Production
Baseline	55	1654	Production Design	–	–
DFIC*	36	1233	Least Difficult	Least Expensive	Most Likely
RFCC	43	1366	Most Difficult	Median	Least Likely
ICKS	44	1486	Median	Most Expensive	Median

*Design Selected for Further Evaluation

Profile and Pattern Factor

The combustor pattern factor and profile factors are non dimensional methods of reporting combustor exit temperatures and temperature distribution. The temperatures at the exit of the combustor are measured with a double-headed thermocouple rake. Each rake consists of five thermocouples arranged radially outward from the inner shell to the outer shell of the combustor. The two rakes are rotated through three hundred and sixty degrees so that both of the two five-element thermocouple rakes traverse the entire exit plane of the combustor. The rake is stepped one hundred times during its traverse of the combustor exit and takes a total of 1000 temperature measurements.

Profile and pattern factor are then computed for each rake as follows:

$$\text{Profile factor} = \frac{\text{Tavg (radial)} - \text{Tavg}}{\text{Tavg} - \text{T3}}$$

Where T avg (radial) is the average temperature read by an individual thermocouple at one radial immersion.

Tavg is the average combustor exit temperature from all five thermocouples

$$\text{Pattern factor} = \frac{\text{Tmax} - \text{Tavg}}{\text{Tavg} - \text{T3}}$$

Where Tmax is the highest temperature read by any of the five thermocouples.

Changes in profile factor affect high pressure turbine bucket life while pattern factor influences high pressure nozzle durability.

All three prototype combustors plus the baseline showed a tendency for pattern factor to increase as hydrogen content decreased. This is attributed to the tendency of the fuels to form carbon deposits in the swirl cups and disrupt the normal spray. Pattern factors changed randomly as fuel air ratio was increased. No trend in any one direction was observed.

The exception to the trend was the #2 Diesel which gave higher pattern factors than ERBS 12.8. This is attributed to the higher boiling range and lower thermal stability of Diesel fuel. No fuel effects on profile factor were noted nor were they expected. There were no observable fuel/air ratio effects on profile factor.

Profile and pattern factor effects unique to the individual combustors are discussed below.

- o Baseline - Profile/Pattern factor plots for the three fuels and JP5 are shown in Figure 15. This combustor basically followed the general trends mentioned above.

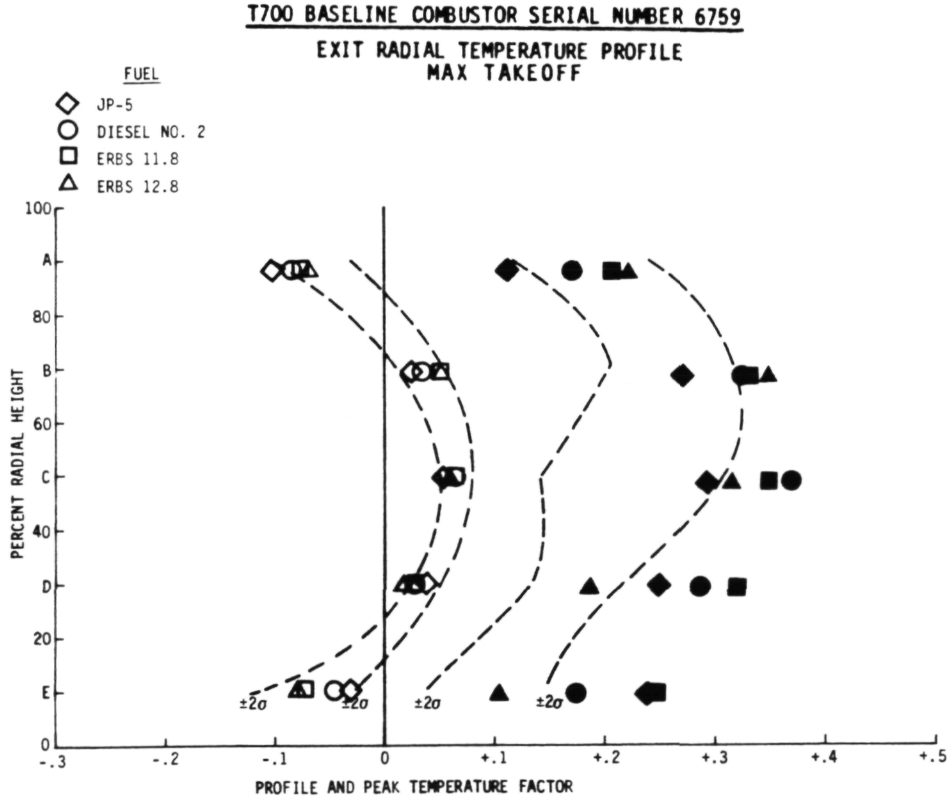


Figure 15. Profile and Pattern Factor, Baseline Combustor (Max Takeoff)

o RFCC - Profile and pattern factor results for the three fuels are plotted in Figure 16. This combustor had the highest pattern factors of all of the combustors tested. This is attributed partially to changes in dilution jet trajectories because of the thimbles, and partially to a high pressure drop (5.0%). The high pressure drop was caused by a missing row of cooling holes on the first inner panel. The missing cooling holes caused the profile factor to shift towards a warmer hub and a cooler tip.

o DFIC - This combustor gave the lowest pattern factors of all of the three combustors. Results are shown in Figure 17. This combustor showed a tendency to form unstable hot streaks from ERBS fuels - especially at the cruise conditions. PTF would intermittently jump to 0.39 and then drop to 0.3. This is attributed to carbon deposits forming in the venturi exits and then falling off. The combustor was operating at 3.2% ΔP at this stage of the program vs 3.85% design ΔP. When this was corrected in the latter part of the test program, the unstable hot streak problem was eliminated.

Profile factor was flatter than baseline and was in fact below the -2 sigma experience level for a production combustor. This is attributed to reduced overpenetration of the dilution jets resulting in more air being deposited at the pitchline.

In addition to being tested with the advanced airblast injectors, the combustor was also tested with production injectors on Diesel Fuel and gasoline. Figure 18A shows profile and pattern factor results on the #2 Diesel using standard and advanced fuel injector. The advanced injectors reduce pitchline profile factor from .045 to .035. The fuel injector related 12th harmonic is reduced by .015 and is shifted 15° (½ cup spacing) as shown in Figure 18B. Pattern factor increased from .26 to .30 going from the standard to the advanced nozzles, but this is believed to be from a carbon deposit. On ERBS 12.8 PTF

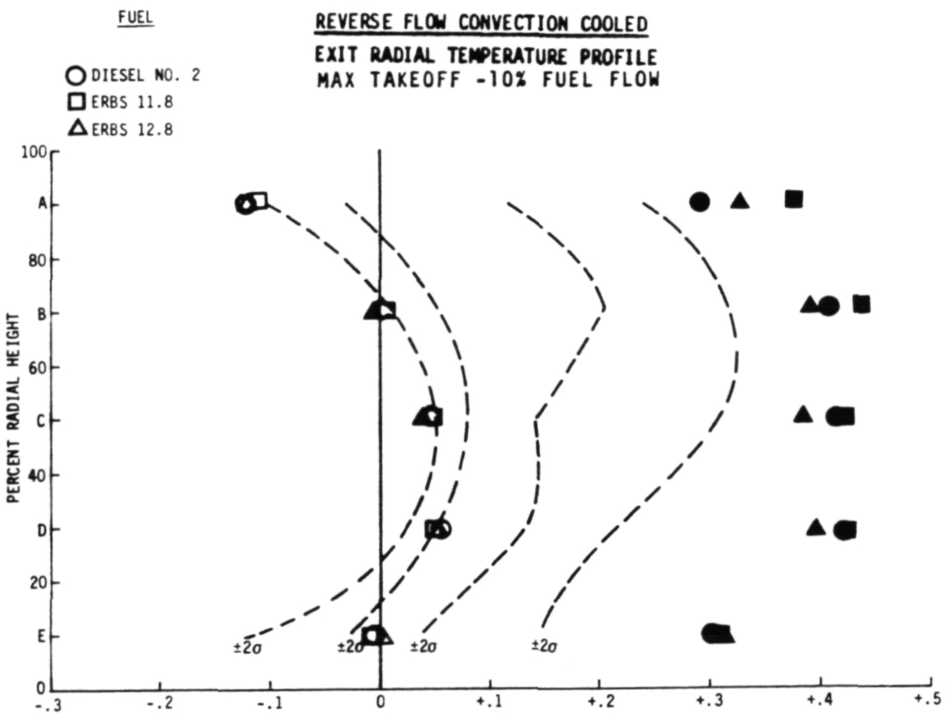


Figure 16. Profile and Pattern Factor RFCC Combustor (Max Takeoff)

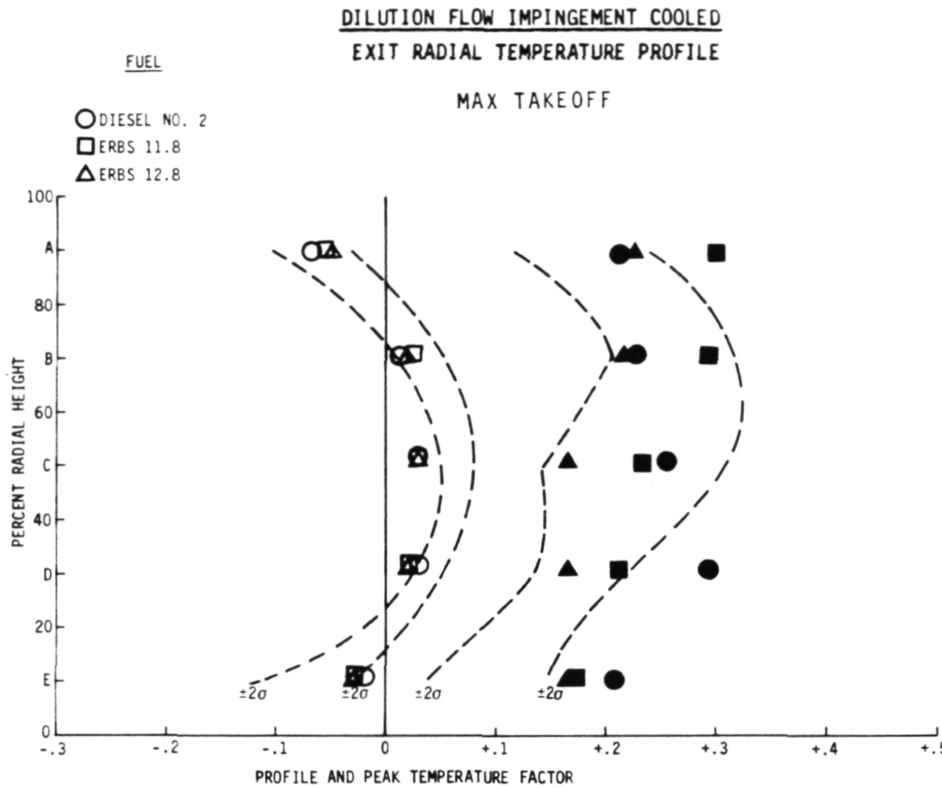


Figure 17. Profile and Pattern Factor, DFIC Combustor (Max Takeoff)

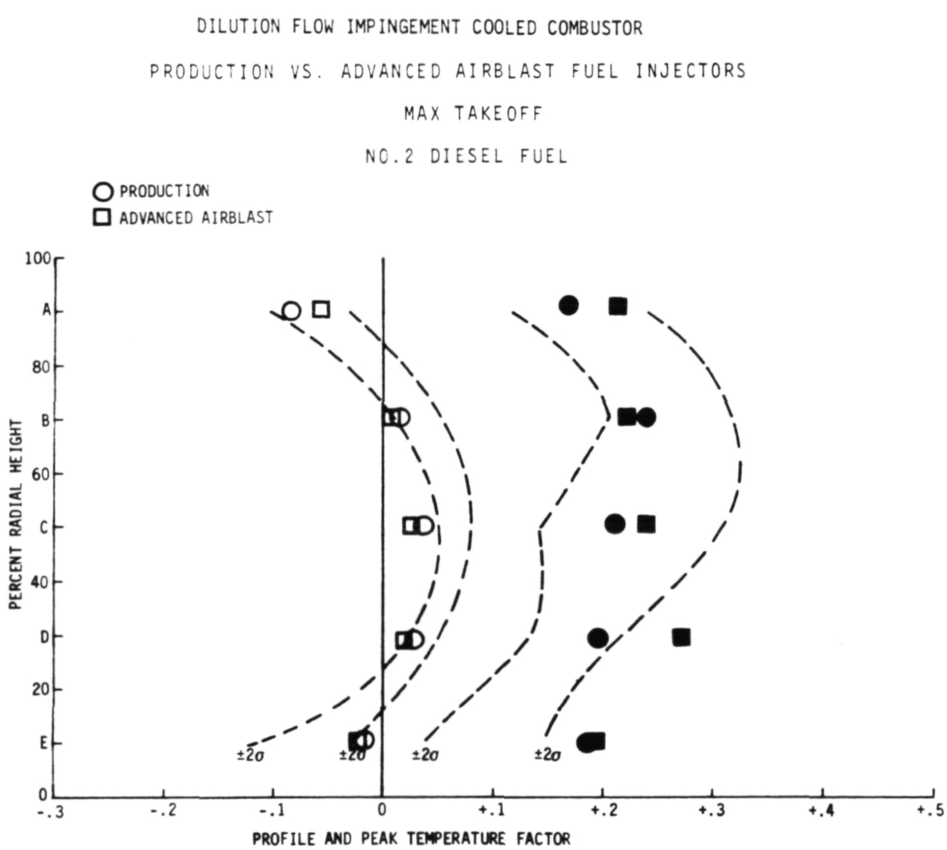


Figure 18A. DFIC Combustor, Profile and Pattern Factor, Production Vs Advanced Airblast Fuel Injectors

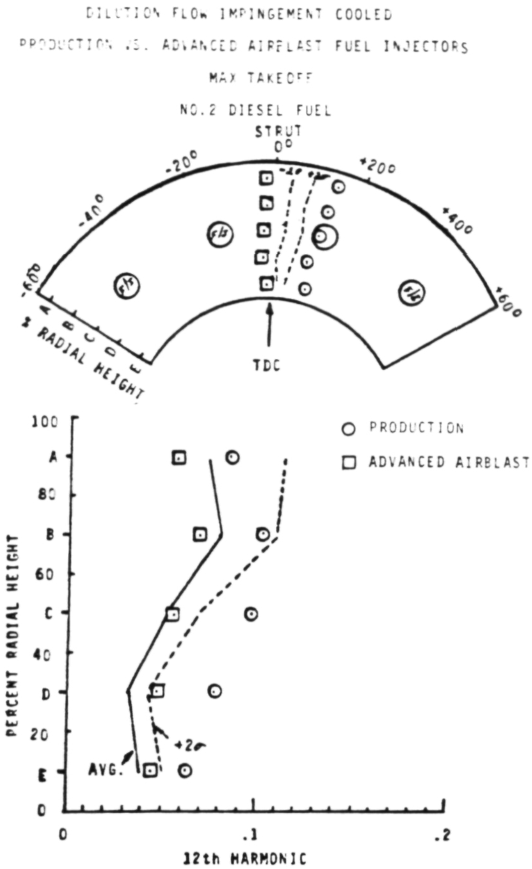


Figure 18B. DFIC Combustor, 12th Harmonic, Production Vs Advanced Airblast Fuel Injectors

was 0.24. The harmonic shift and lower pitchline profile are attributed to the hollow spray of the advanced airblast injector versus the solid spray on the production injector (Figure 10). This results in more fuel being deposited at the outboard immersions and between cups, and less fuel at the pitchline.

After being reworked to design ΔP for the final parametric tests, profile factor shifted towards a warmer hub and a cooler tip. Profile and pattern factor results for ERBS 12.8 before and after the rework are shown in Figure 19.

Post rework profile and pattern factor results for the fuels are plotted in Figure 20. Pattern factors on #2 Diesel, ERBS 12.8 and ERBS 11.8 were .26, .22, and .27 respectively. Pattern factor on this combustor showed the least sensitivity to fuel effects of any of the configurations including baseline. The high transient pattern factors observed on the previous test of this combustor were absent. The increased ΔP apparently reduces carbon formation in the swirl cups. Post test inspection showed minimal carbon buildup. The advanced injector provides a means of minimizing the fuel effect on pattern factor.

o ICRS - Profile and Pattern factors were within production experience. This combustor showed a stronger tendency than the baseline for increased pattern factor with decreasing hydrogen. Profile and Pattern factors for the three fuels are plotted in Figure 21.

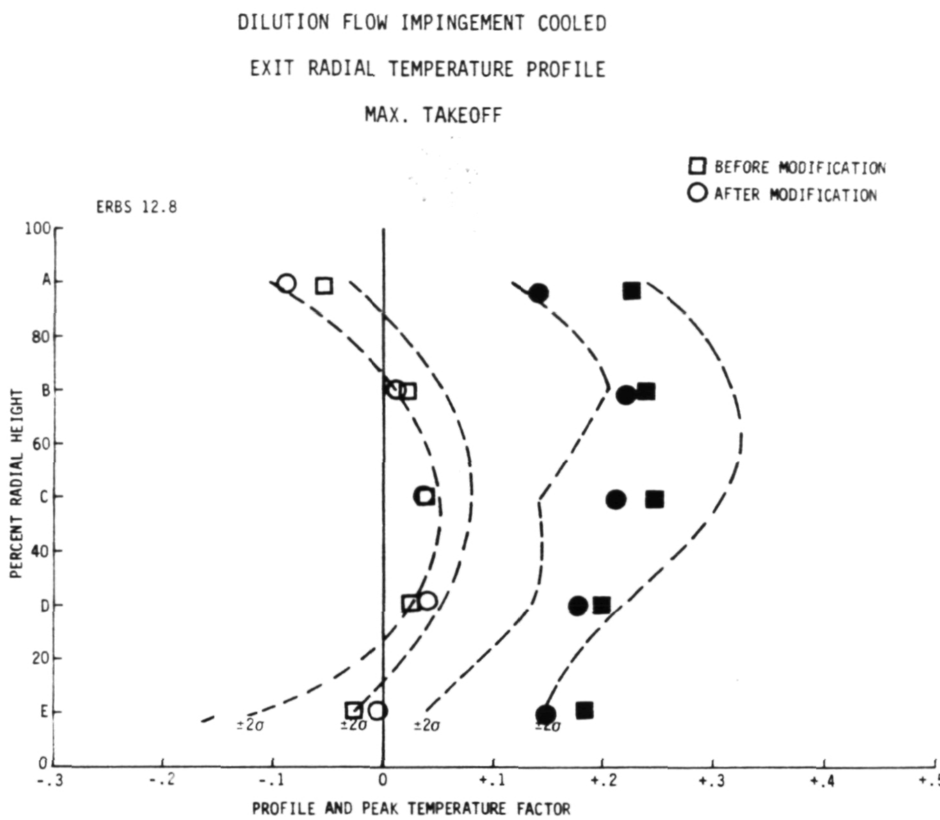


Figure 19. Profile and Pattern Factor Comparison Before and After Modification

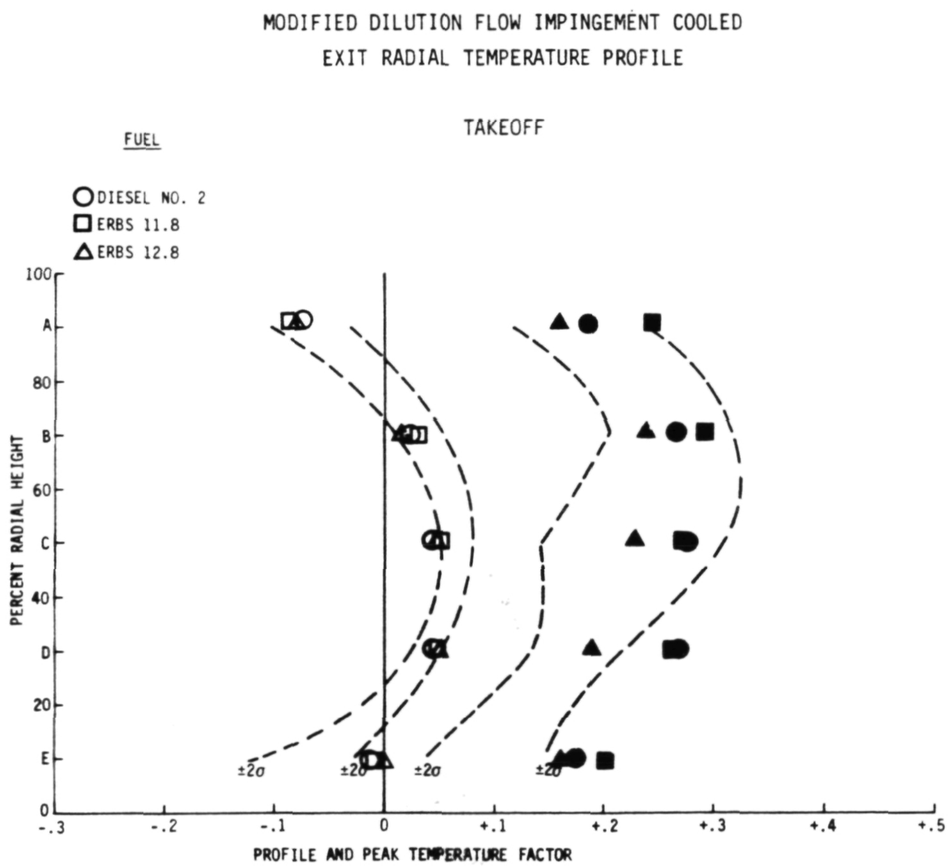


Figure 20. Profile and Pattern Factor, Modified DFIC Combustor, Three Fuels, Max Takeoff

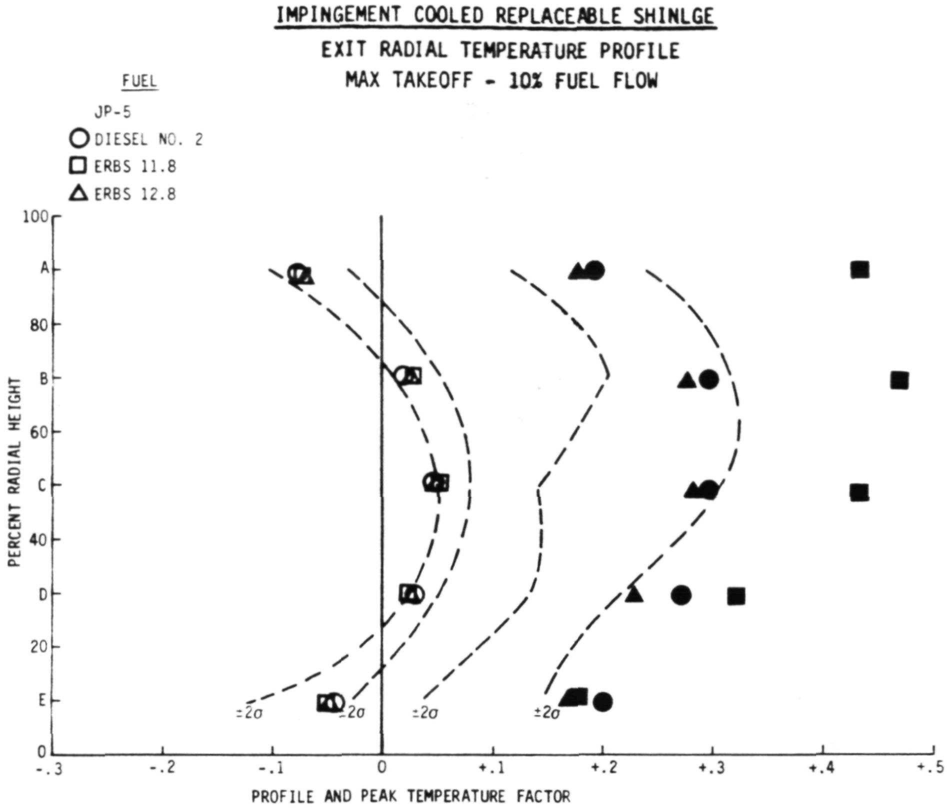


Figure 21. Profile and Pattern Factor ICRS Combustor, Max Takeoff

Smoke

Smoke was measured using two methods - the ARP 1179 smoke spot method, and a weighed particulate sample. The comparisons were made using the particulate based smoke numbers as the ARP1179 data has historically been unreliable for component rig tests, due to the effects of high pressure causing condensation of moisture in the sample lines. The ARP 1179 data will be presented as it is still necessary to use it where particulate data is not available.

Because the combustors all deviated significantly from the design 3.85% ΔP, a correction had to be derived to effect a valid comparison of the three designs. Figure 22 shows the experience band of cumulative GE smoke experience for all engines correlated to baffle face fuel air ratio. Smoke numbers were corrected to the nominal 3.85% ΔP condition by assuming that the smoke vs fuel/air relationship followed the same slope as the GE experience bands.

Particulate based smoke number vs % hydrogen is plotted in Figure 23. The corresponding ARP1179 data is shown in Figure 24.

Raw and corrected smoke data are tabulated in Table 5.

Raw smoke numbers are plotted on the GE smoke experience bands in Figure 25. ERBS 11.8 and 12.8 both follow a slightly shallower slope than the GE experience bands. ERBS 11.8 also gave a 55 smoke number vs a predicted value of 50. The consequence of this is that the ERBS fuels require more leaning out of the dome than was proposed for this program in order to meet the smoke objective.

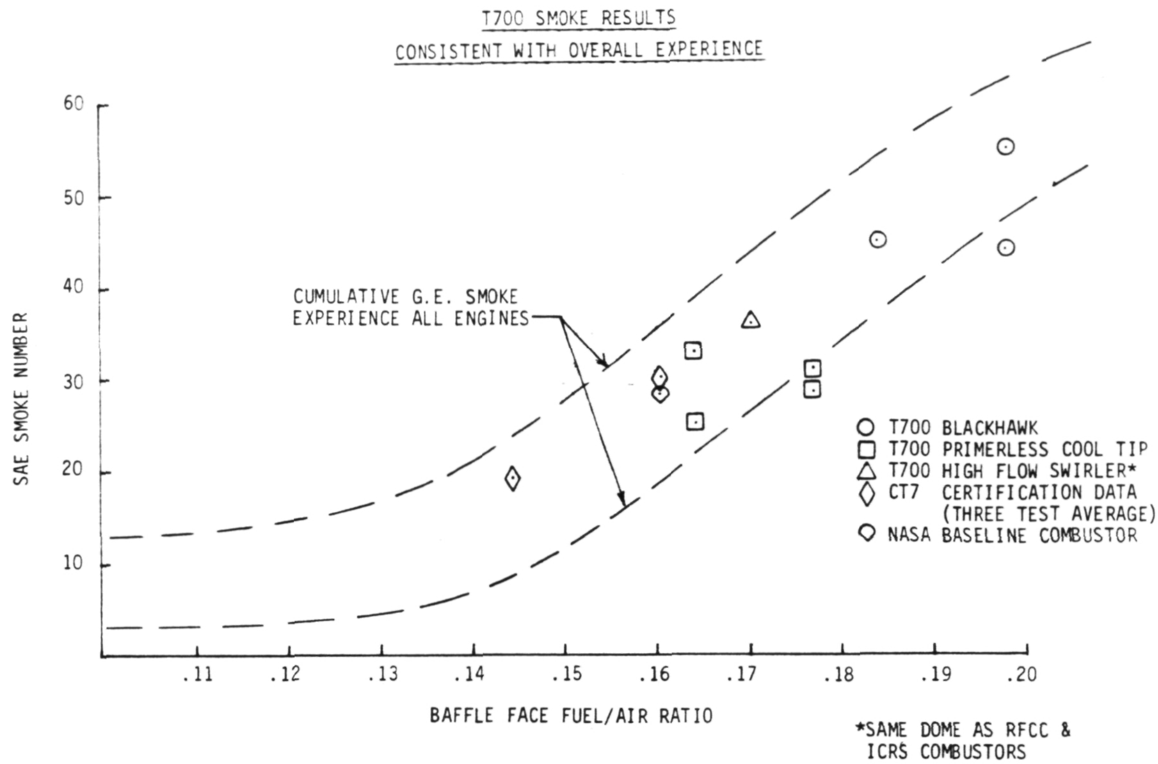


Figure 22. Smoke Vs Baffle Face Fuel-Air Ratio-Overall GE Experience

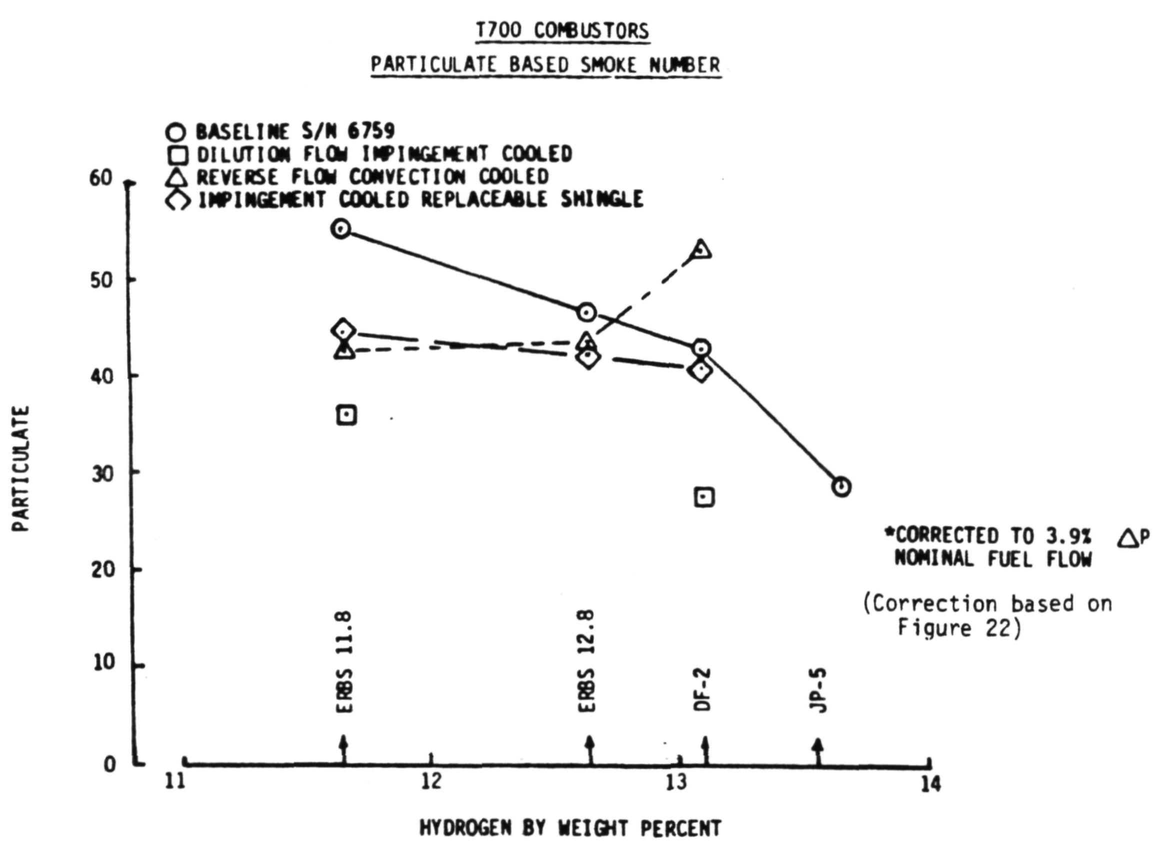


Figure 23. Particulate Based Smoke Vs % Hydrogen, Four Combustors

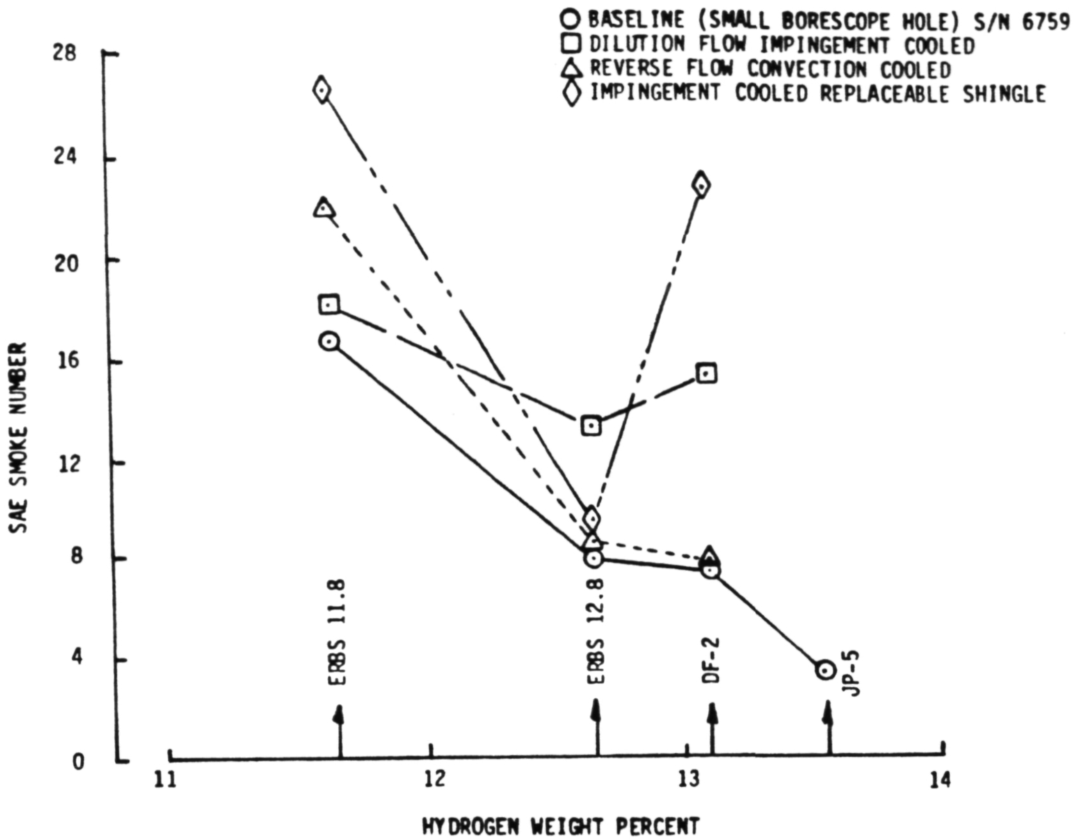


Figure 24. ARP1179 Smoke, Max Takeoff, Four Combustors

TABLE 5
Tabulated Raw Smoke and Baffle Face Fuel Air Ratio Data

Combustor	Test S12-	Fuel	$\frac{\Delta P^*}{P}$	PPS	$\%W_4$ Baffle Face	$\dot{W}$** Baffle Face	W_f PPH	F/A Baffle Face	Particulate Based Raw Smoke #	Corrected Smoke #
Baseline	001	JP5	3.85	6.877	17.08	1.175	683	.1614	27.5	27.5
	001	#2 Diesel	3.85	7.559	17.08	1.291	751	.1615	42.5	42.5
	003	ERBS 12.8	3.85	7.528	17.08	1.286	750	.1620	46.5	46.5
	004	ERBS 11.8	3.85	7.455	17.08	1.274	713	.1555	48	55
DFIC	005	ERBS 12.8	3.25	6.928	16.61	1.151	678	.1635	--	--
	006	ERBS11.8	3.25	6.841	16.61	1.136	676	.1651	47	36.0
	007	#2 Diesel	3.25	6.829	16.61	1.134	678	.1659	43.5	27.5
RFCC	008	#2 Diesel	5.0	6.835	21.60	1.476	681	.1280	47.5	53.2
	009	ERBS 12.8	5.0	6.890	21.60	1.488	680	.1269	36	43.5
	010	ERB 11.8	5.0	6.898	21.60	1.490	680	.1267	33	42.5
ICRS	011	#2 Diesel	3.35	7.47	17.80	1.331	751	.1567	50	40.5
	012	ERBS 12.8	3.35	7.529	17.80	1.341	757	.1568	48.5	41.5
	013	ERBS 11.8	3.35	7.477	17.80	1.331	755	.1575	49.5	44.2
Modified DFIC	014	ERBS 11.8	3.85	7.651	18.00	1.377	764	.1540	47.8	40
	015	ERBS 12.8	3.85	7.432	18.00	1.338	778	.1615	55	47
	016	#2 Diesel	3.85	6.868	18.00	1.236	676	.1519	--	--

* At $\left(\frac{W\sqrt{T3}^2}{P}\right) = 1.26$

**Includes 1/2 of first panel dilution flow

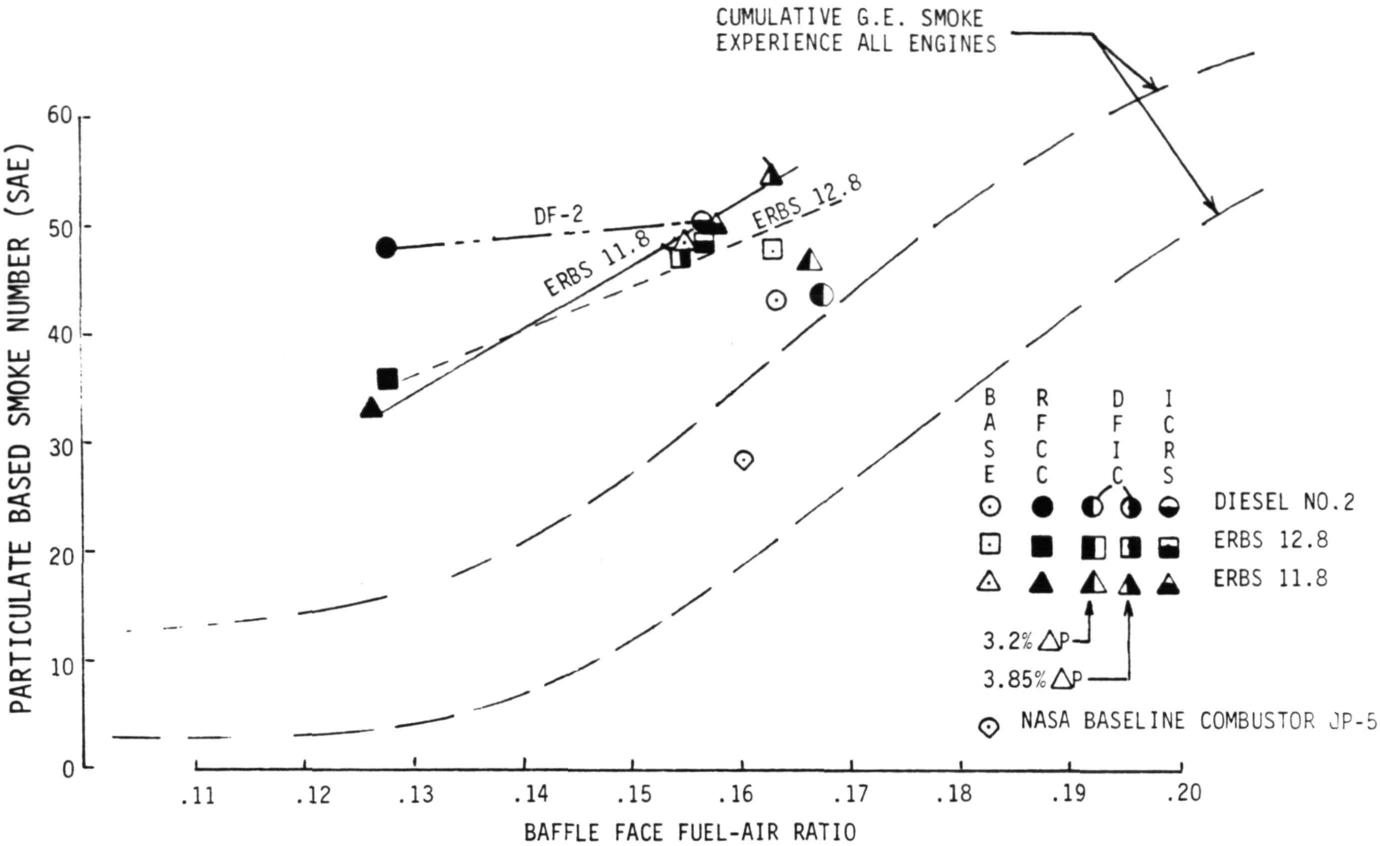


Figure 25. NASA Smoke Results Vs Baffle Face Fuel-Air Ratio

Because of its high pressure drop, the RFCC liner ran with a baffle face fuel air ratio of .128 vs a design objective of .145. Raw smoke numbers on this combustor met the objectives on the ERBS fuels but smoke was actually worse than baseline on #2 Diesel fuel. A baffle face fuel air ratio of around 0.128 is what is actually required to meet the smoke objective on ERBS 11.8.

The DFIC combustor at 3.2% ΔP indicated sufficient improvement over the baseline combustor, when smoke numbers were corrected to 3.85% ΔP, to meet the objective on all fuels. The Diesel fuel results were of particular importance here as Diesel fuel is being seriously considered as an alternate fuel for the T700. This was the only one of the three liners that indicated any improvement in smoke for Diesel fuel based on initial screening tests. The two lean dome concepts, in fact, indicated a deterioration in Diesel fuel smoke performance.

For the final parametric evaluation, the ΔP for the DFIC combustor was increased by closing off one row of impingement holes on the inner and outer shells. When the smoke measurements were repeated, the results were disappointing. There was no reduction in smoke for the ERBS fuels due to increasing dome ΔP. The ERBS data fell in on the smoke vs baffle face fuel air ratio lines from the other combustors. The Diesel fuel data was lost. ARP1179 data, however, indicated an improvement from the previous Diesel fuel test of this combustor from 15.3 to 9. Due to the aforementioned problems with this method on component rig tests we are reluctant to put a number on the degree of improvement, but we do feel that there was a real improvement in smoke for Diesel fuel.

The smoke data from the three combustors implies the following conclusions:

- o There are two different smoke forming mechanisms being observed:
  - Droplet burning with smoke being formed by pyrolisis of liquid fuel droplets and locally rich diffusion buring around the droplet.
  - Rich gas phase burning of vaporized fuel
- o With Diesel Fuel, the droplet burning mechanism dominates due to its higher boiling range and lower thermal stability. This is why Diesel fuel responds more favorably to improved atomization from the advanced injection than it does to simple leaning out of the dome. The poor response to the lean dome concept may actually imply a slight deterioration in atomization from the altered primary/secondary venturi flow split.
- o With ERBS Fuels, the gas phase reactions dominate. This is why the ERBS fuels respond better to changes in dome stoichiometry than to improved atomization. All of the dome concepts tested atomize these fuels to the degree that no further improvement from atomization is likely. It's possible that optimum atomization on ERBS fuels with the advanced airblast system was achieved at the 3.2% ΔP condition and that at 3.9% ΔP the fuel was "overatomized" and burning too close to the fuel injector tips, with a resultant deterioration in smoke performance relative to dome stoichiometry.
- o The ERBS fuels require more leaning out of the dome than was originally proposed for this program in order to meet the smoke objective.
- o An "all fuels" combustor, which would operate satisfactorily on ERBS and Diesel fuels will require a combination of lean dome and advanced airblast fuel injection.

Metal Temperatures

As expected an increase in metal temperatures was observed with the broad spec fuels. The highest first panel temperature on the baseline was 1634°F on ERBS 11.8 vs 1380°F on JP5. Although there were no obvious signs of liner distress after component test, the increase in metal temperature was sufficient to predict an 0.2:1 reduction in cyclic life.

First panel metal temperatures vs % hydrogen are plotted for all four combustors in Figure 26. Metal temperatures for all panels are tabulated in Table 6. All of the combustors ran sufficiently cooler than the baseline combustor to completely negate the fuel effects; however, the DFIC combustor was the coolest of the three.

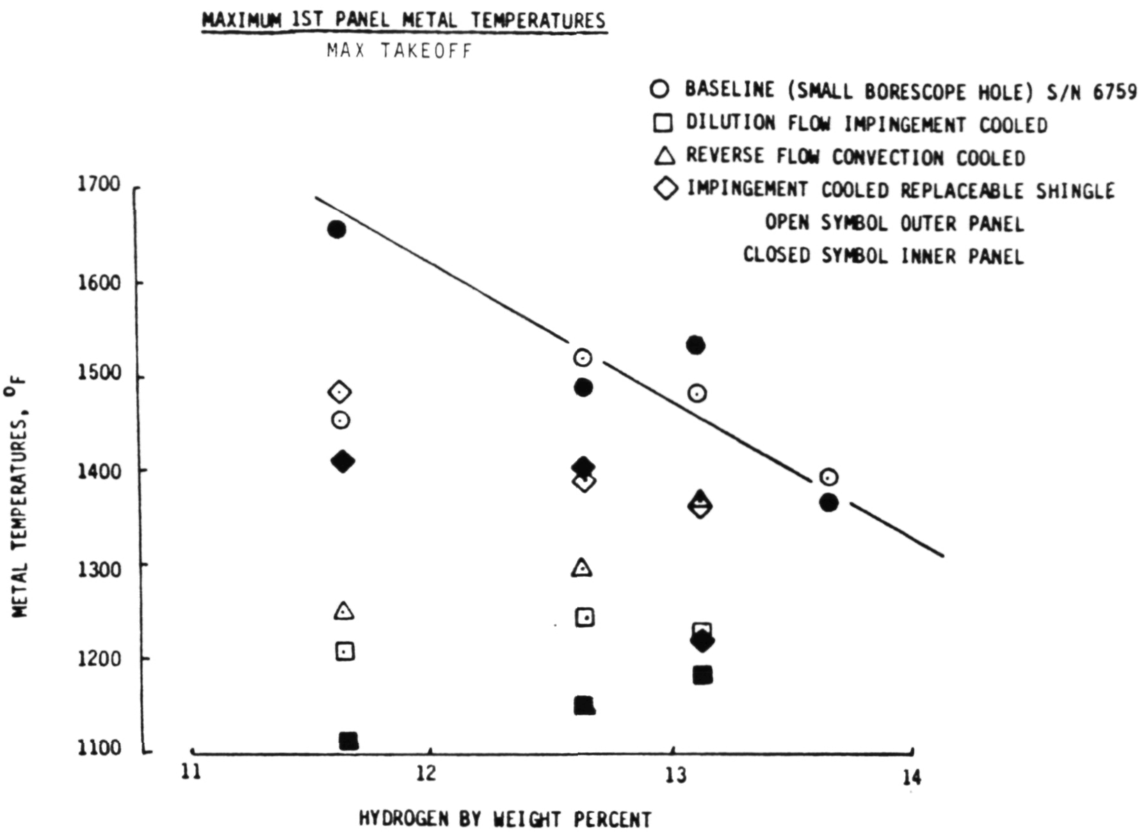


Figure 26. First Panel Metal Temperature Vs Hydrogen, Four Combustors, Max Takeoff

TABLE 6
Peak Metal Tempertures, of 4 Combustors, 3 Fuels, All Panels

Location		Baseline			Reverse Flow Convection Cooled*			Dilution Flow Impingement Cooled			Impingement Cooled Replaceable Shingle		
	JP-5	DF-2	ERBS 12.8	ERBS 11.8	DF-2	ERBS 12.8	ERBS 11.8	DF-2	ERBS 12.8	ERBS 11.8	DF-2	ERBS 12.8	ERBS 11.8
Point S1200B-Cruise													
Panel 1 Outer	1360	1378	1304	1410	1207	1195	1280	1186	1262	1228	1273	1309	1441
Panel 1 Inner	1395	1368	1381	1451	1569	1455	1625	1205	1336	1267	1411	1230	1356
Panel 2 Outer	1355	1353	1374	1538	1216	1198	1396	1070	1057	1341	1347	1366	1502
Panel 2 Inner	1206	1300	1268	1298	1268	1190	1409	1173	1164	1234	1185	1254	1412
Panel 3 Outer	1196	1199	1237	1334	1133	1109	1205	1026	1031	1146	1337	1379	1457
Panel 3 Inner	1151	1145	1177	1208	1224	1243	1380	1146	1113	1139	1117	1130	1174
Point S1300B IRP													
Panel 1 Outer	1380	1380	1409	1349	1313	1248	1248	1151	1243	1183	1384	1389	1486
Panel 1 Inner	1363	1511	1466	1634	1576*	1631*	1621*	1191	1235	1254	1220	1307	1345
Panel 2 Outer	1374	1462	1491	1448	1277	1309	1350	1219	1164	1210	1399	1408	1518
Panel 2 Inner	1241	1336	1323	1321	1296	1336	1395	1195	1178	1239	1171	1190	1191
Panel 3 Outer	1211	1255	1276	1246	1166	1203	1206	1116	1082	1104	1422	1403	1539
Panel 3 Inner	1163	1178	1207	1198	1256	1353	1379	1126	1118	1149	1306	1127	1182

*First inner panel temperature is high because of manufacturing error and, therefore, not used for comparison.

The first panel of the DFIC Combustor ran 100-150°F cooler on ERBS 11.8 than the baseline did on JP5. Test results indicate a negative fuel effect; i.e., the combustor ran cooler as hydrogen decreased. This is probably not real, but the consequence of the worst hot streaks not always being near a thermocouple. It does seem reasonable to say that metal temperatures on this combustor are insensitive to properties of the fuels selected for this study.

Following rework of this combustor to the design pressur drop, metal temperature measurements were repeated during final parametric testing. The results tabulated in table 7 show are similar to those obtained during the screening tests.

The RFCC combustor ran 100-150°F cooler on ERBS 11.8 than the baseline did on JP5. This combustor also proved to be insensitive to the fuel properties.

The ICRS combustor duplicated the baseline combustor JP5 metal temperatures when running on ERBS 11.8. This combustor thus negates adverse fuel effects on the basis of metal temperature alone. The shingled design provides a further life improvement by minimizing thermal stresses.

Gaseous Emissions

As the screening points were all at high power, HC and CO gaseous emissions were very low. Variations were mostly from combustor to combustor with minimal fuel effect or fuel/air ratio effect.

- HC emissions were too low to measure;
- CO emissions showed no clear cut fuel or fuel/air effect;
- NO_x showed a slight tendency to decrease with increasing fuel/air ratio.

NO_x and CO emission results are shown in Figures 27 and 28. CO emissions from all of the experimental combustors were higher than for the baseline combustors. The DFIC and RFCC combustors, which had the lowest metal temperatures had the highest CO levels. The ICRS combustor, which had somewhat higher metal temperatures than the DFIC and RFCC combustors, was midway between the baseline and the DFIC and RFCC combustors. The lowered metal temperatures may be causing increased wall quenching and thus slightly higher CO levels.

TABLE 7
Peak Metal Temperatures, Modified DFIC Combustor

Location	Cruise			Max Continuous			Max Takeoff		
	#2D	ERBS 12.8	ERB 11.8	#2D	ERBS 12.8	ERBS 11.8	#2D	ERBS 12.8	ERBS 11.8
Panel 1 Outer	1188	1099	1177		1231	1324	1160	1185	1261
Panel 1 Inner	1252	1175	1226		1204	1188	1158	1238	1086
Panel 2 Outer	1228	1138	1094		1167	1268	1150	1193	1286
Panel 2 Inner	1144	1130	1232		1234	1258	1258	1202	1277
Panel 3 Outer	1132	1069	1044		1118	1166	1163	1150	1118
Panel 3 Inner	1171	1172	1138		1180	1193	1172	1231	1183

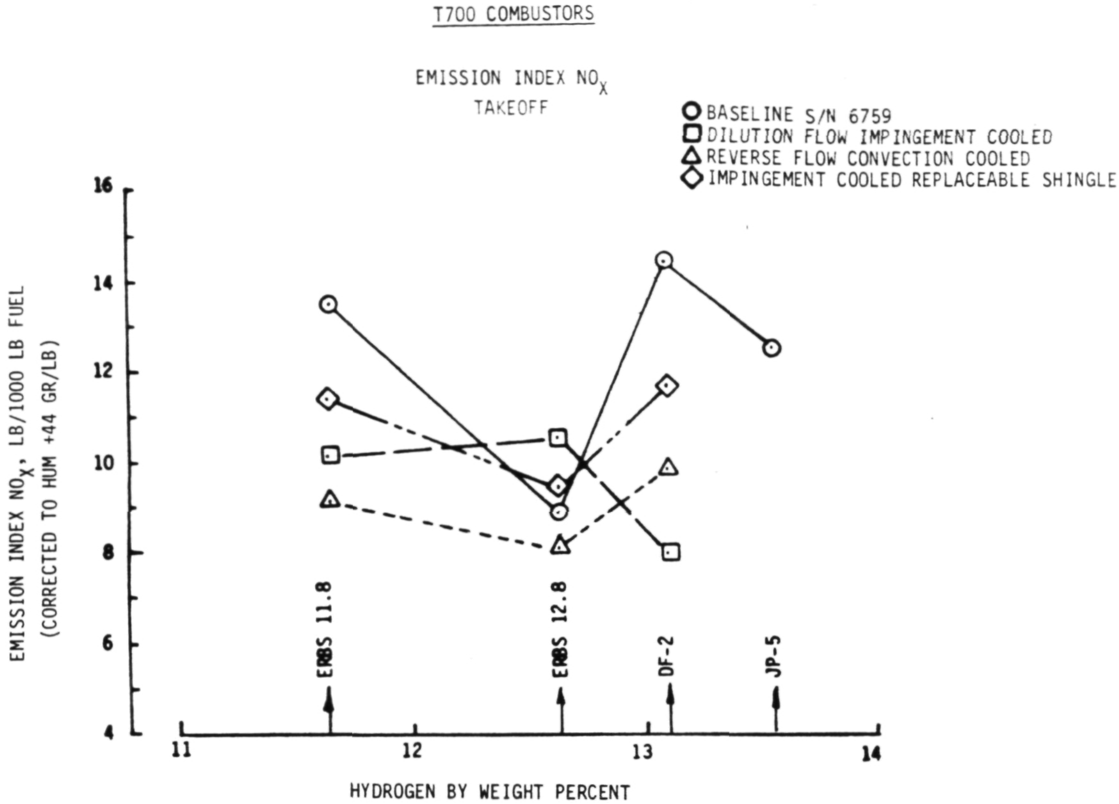


Figure 27. Emission Index NO_X Vs Hydrogen, Four Combustors (Takeoff)

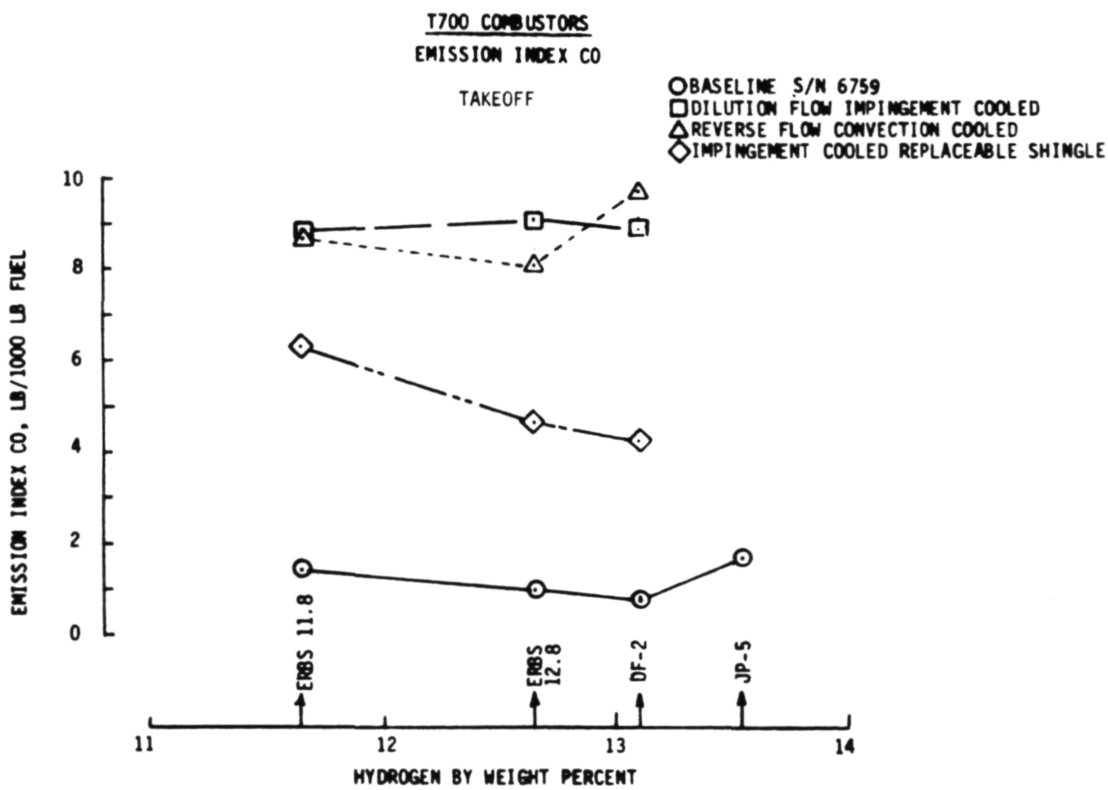


Figure 28. Emission Index CO Vs Hydrogen, Four Combustors (Max Takeoff)

During the final parametric testing phase on the DFIC Combustor, the emission analyzers suffered numerous problems resulting in the loss of some of the data. NO_X analyzer failed during the second half of the ERBS 11.8 test, so NO_X data for half of the ERBS 11.8 testing and the #2 Diesel testing was lost.

Calibration data for the CO analyzer showed inconsistent response, so this data is only good for rough estimates of relative CO levels.

Gaseous emissions for the final parametric test phase on the DFIC Combustor are tabulated in Table 8. High power results were essentially a repeat of the screening test data. Idle HC and CO data indicates idle efficiencies in excess of 98%, consistent with production T700.

Flame Radiation

Flame radiation results are shown plotted in Figure 29 and tabulated in Table 9. The results show wide variability between combustors, but the same general trends relative to % hydrogen and fuel/air ratios.

- Radiation increased with decreasing % hydrogen (Figure 29)
- Radiation decreased with increased fuel/air ratio.

The second result was unexpected, but consistent with all four combustors. The most plausible explanation is that the radiometer is looking through an incompletely reacted, inhomogeneous mixture. Radiation is being reduced by unburned carbon particles and pyrolyzing fuel droplets plus the fact that full adiabatic flame temperature has not been achieved at this point in the combustor. This effect would become more severe as fuel/air ratio increased thus causing lower radiation readings. The fact that we are looking at localized inhomogenities with a narrow angle radiometer would explain the variability between combustors and the decreasing radiation readings when wall temperatures would indicate an increase.

The results would indicate that the radiometer geometry should be altered to view a zone where the reactions are more completely established. Currently we are viewing the forward most part of the flame front, which is sensitive to variations in fuel/air ratio as well as part to part variability. Although the current radiometer configuration is satisfactory for relative comparisons for fuel effects, the absolute numbers are not reliable.

Overspeed Protection Condition - LBO Performance

The lean blowout fuel flows for the overspeed protection conditions are shown plotted vs % hydrogen in Figure 30. The DFIC combustor falls short of the acceptability limit for T700 combustors on ERBS Fuels but gives acceptable results on #2 Diesel. This may indicate a slight fuel effect on lean blowout performance.

TABLE 8

Gaseous Emissions And Idle Efficiency-Dilution Flow Impingement Cooled Combustor

Test	Fuel	Point	EI HC	EI CO	EI NO_x	CO2%	Idle Efficiency
S12014	ERBS 12.8	Cruise	0	-	14.027	-	
		Max Cont.	0	-	-	-	
		Max Takeoff	0	-	12.9	7.0	
		Idle	1.464	5.96 (est)	3.92	3.4	99.7
S12015	ERBS 11.8	Cruise	-	-	2.8	-	
		Max Cont.	0	-	-	2.5	
		Max Takeoff	0	-	-	-	
		Idle	NO DATA	-	-	-	-
S12016	#2 Diesel	Cruise	0	-	-	6.3	
		Max Takeoff	0	-	-	6.3	
		Ilde	2.02	8.181 (est)	-	3.2	99.6

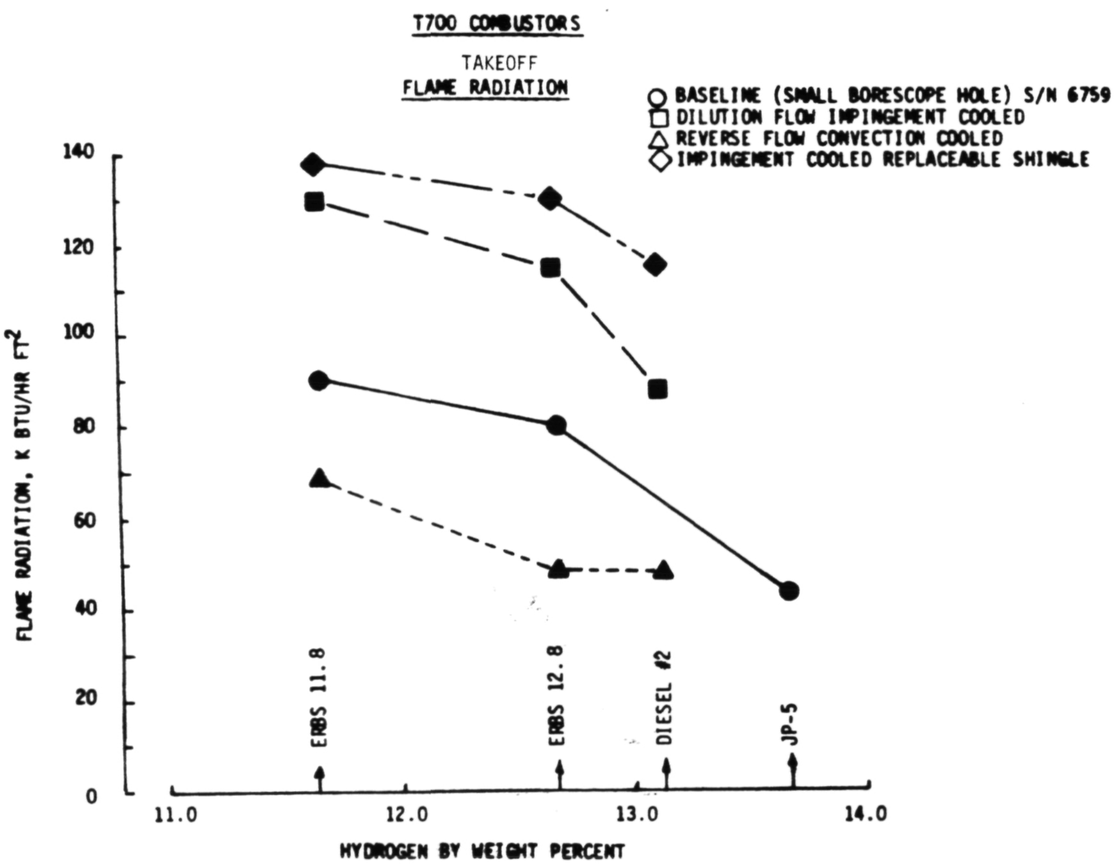


Figure 29. Flame Radiation Vs Hydrogen By Weight Percent, Four Combustors (Takeoff)

TABLE 9
TABULATED RADIATION DATA

Combustor	Test	Fuel	Radiation $\frac{KBTU}{Hr\ Ft^2}$ Cruise -10% w_f	Cruise Nominal w_f	Cruise +10% w_f	Max Takeoff -10% w_f	Max Takeoff Nominal w_f	Max Takeoff +10% w_f
Baseline	S12001	JP5	33	26	24.5	42	34	32
	S12002	#2Diesel		64	50	43		
	S12003	ERBS12.8	68	63	53	80	73	
	S12004	ERBS11.8	74	59	68	84	90	
DFIC	S12005	ERBS12.8	87	84	68	92	115	79
	S12006	ERBS11.8	105	95	100	125	130	127
	S12007	#2Diesel		76	70	68	84	88
RFCC	S12008	#2Diesel		43	43	45	43	45 4
	S12009	ERBS12.8	41	36	40	41	46	48
	S12010	ERBS11.8	67	76	64	67	54	68
ICRS	S12011	#2Diesel	88	76	80	115	87	64
	S12012	ERBS12.8	95	89	89	130	110	98
	S12013	ERBS11.8	112	99	79	138	115	98

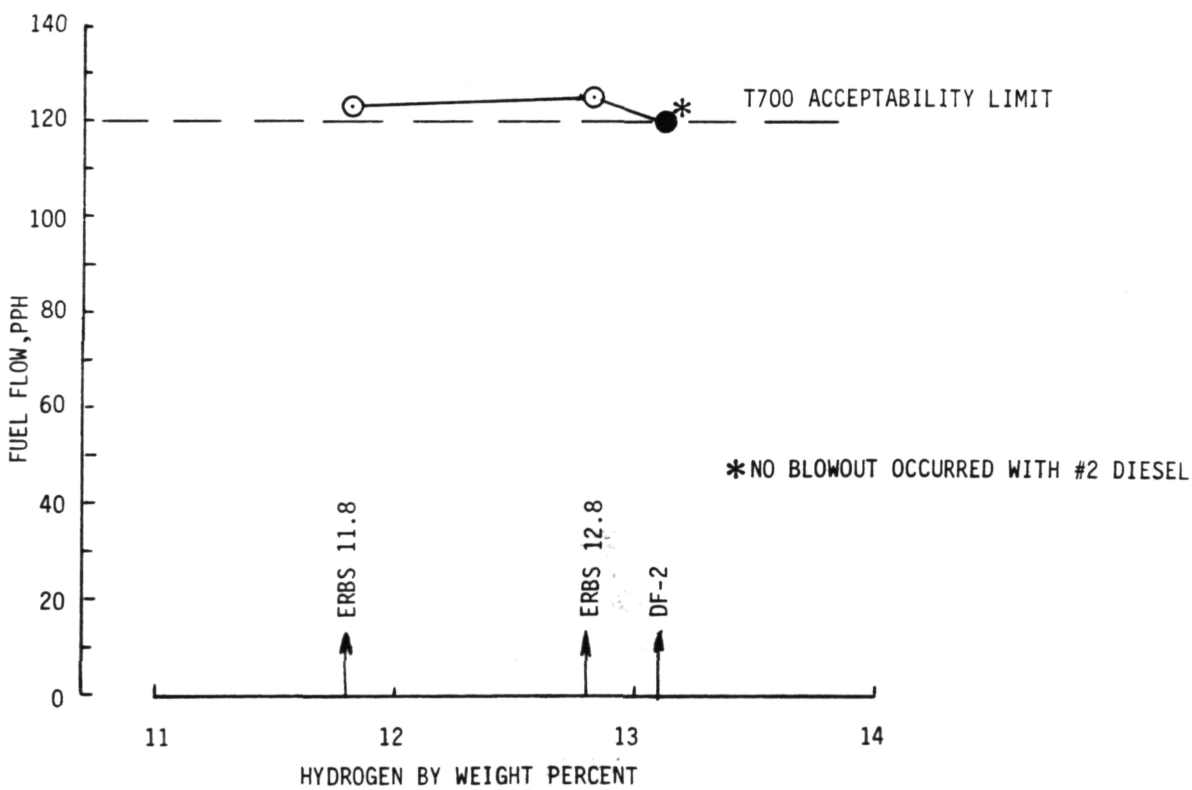


Figure 30. Lean Blowout Fuel-Air Ratio Vs Hydrogen By Weight Percent

Lightoff/LBO Performance

Figure 31 shows lightoff fuel flow vs θ (Longwell parameter). Sea level lightoff is acceptable for all fuels although lightoff fuel/air ratios on ERBS 11.8 and #2 Diesel were higher than for ERBS 12.8. Altitude lightoff shows a deterioration from production T700 levels in that 20000 ft altitude lightoff is marginal with poor propagation between cups vs a reliable lightoff for production T700.

Lightoff data is tabulated in Table 10. ERBS 11.8 altitude lightoff was not achieved due to power supply problems in the ignition system.

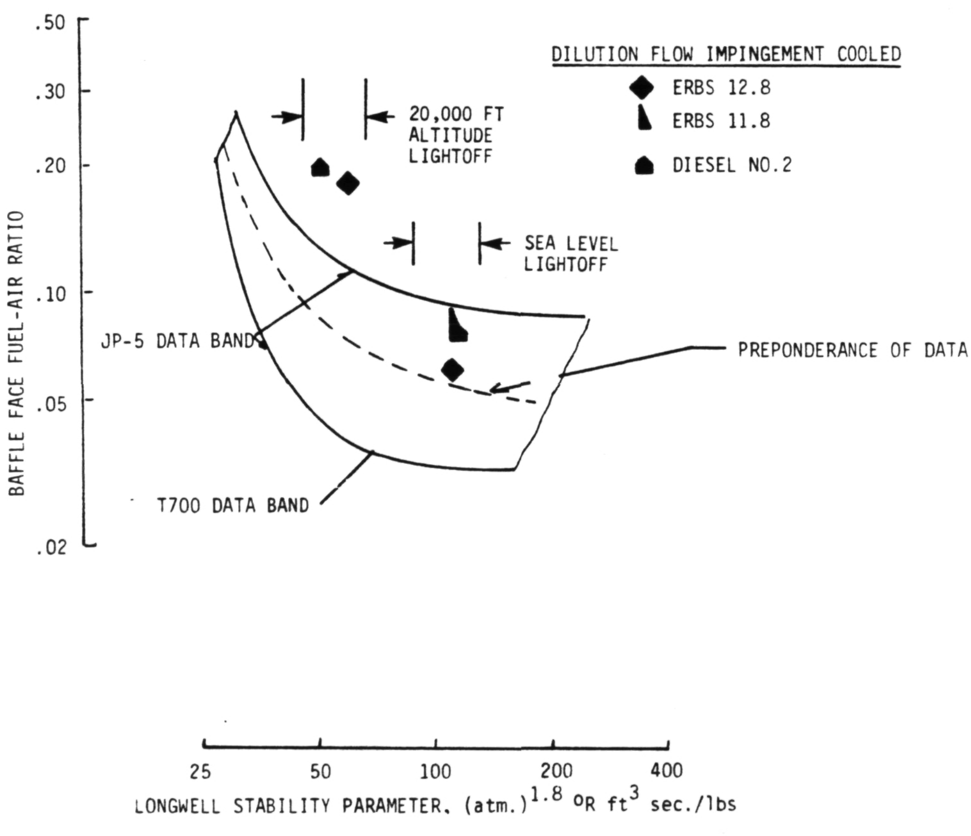


Figure 31. Modified DFIC Combustor, Advanced Airblast Fuel Injectors, Lightoff Performance

TABLE 10
Tabulated Lightoff Data

Fuel Combustor	W3 PPS	W4 PPS	P3 IN HGA	T3 °R	Wf L/O PPH	Wf LBO PPH	θ	Time to Light Sec	f/A Combustor	f/A Baffleface
					Sea Level Lightoff					
ERBS 12.8	1.27	.984	51.89	559	40	38	112.7	3	.0113	.062
ERBS 11.8	1.19	.922	50.6	553	50	47	113.8	4	.015	.083
#2D	1.11	.86	50.9	536	44	39	119.5	9	.014	.078
					20,000 Ft Lightoff					
ERBS 12.8	.56	.434	24	544	51	45	62.1	6	.033	.181
ERBS 11.8	N0 Light on ERBS 11.8 Due to Power Supply Problems									
#2D	.64	.496	23	533	62	65	49.3	5	.035	.192
					Idle Lightoff					
ERBS 12.8	2.79	2.16	114	869	115	70	329	1	.0147	.0785
ERBS 11.8	2.53	1.96	115	870	80	76	369	2	.0113	.062
#2D	2.81	2.18	115	869	110	53	332	32	.0140	.0768

$$\theta = \frac{ATM^{1.8}\ {}^{\circ}R\ ft^3}{lb/sec}$$

$V_{combustor} = .074\ ft^3$

Idle Efficiency

Idle efficiency was greater than 98% for all fuels, which is in the range of production T700. No fuel effect was noted for idle efficiency.

OVERALL RESULTS

The two primary objectives of this program were controlling metal temperatures and smoke with low hydrogen fuels.

All three combustors reduced metal temperatures sufficiently to negate any life reduction from low hydrogen fuels. The Dilution Flow Impingement Cooling concept was chosen because it provides the lowest metal temperatures with the least amount of complication. The shingled combustor concept is still promising for its ability to use materials such as ceramics for the shingles. The disassembly feature would make this a good vehicle for evaluating such materials as a future program.

Smoke reduction fell short of objectives although the 5% Δ P on the RFCC combustor enabled us to determine what was necessary to achieve those objectives. Additional leaning out of the dome is necessary to meet the objective on ERBS fuels but the advanced airblast injection appears necessary for Diesel fuel. A combination of high flowing swirlers and advanced airblast injectors appears necessary for a combustor that will operate satisfactorily on all three fuels. Part of the additional airflow can be achieved by further modification to the fuel nozzle.

These designs showed slight deterioration of lightoff and lean blowout performance margin. Further smoke reductions will aggravate this problem. Some of GE's large commercial engines use locally rich cups over the igniters to offset this. This is preferred over sector burning or variable geometry for the degree of enrichment required.

Based on the results of this program, the following concepts show the most promise for a combustor that would handle ERBS fuels and #2 Diesel fuel:

- Advanced Airblast fuel injection with a lean dome for smoke control on ERBS fuels and Diesel fuels.
- Dilution Flow Impingement Cooling the combustor liner to achieve 5000 hour life on all fuels.