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Analytical Fuel Property Effects - Small Combustors (Phase 1)

Contract NAS3-22829

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By

J. D. Cohen

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Lewis Research Center
21000 Brookpark Road, Cleveland Ohio 44135

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Lynn, Mass.

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16 Abstract

An analytical study was made of the effects of nonstandard aviation fuels on a typical small gas turbine combustor. The T700/CT7 engine family was chosen 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.

The study anticipated higher than normal smoke output and flame radiation intensity for the current T700 combustor which serves as a baseline. It is, therefore, predicted that out of specification smoke visibility and higher than normal shell temperatures will exist when using NASA ERBS fuels with a consequence of severe reduction in cyclic life.

Three new designs are proposed to compensate for the deficiencies expected with the existing design. They have emerged as the best of the eight originally proposed redesigns or combinations thereof. After the five choices that were originally made by NASA on the basis of competing performance factors, General Electric narrowed the field to the three proposed.

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SUMMARY

The study performed in Phase I 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 study 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 delivery schedules or aromatics content which might affect fuel system seals.

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 2) 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 moderately rich primary zone which happens to be relatively sensitive to aromatics fractions carried in the fuel in terms of smoke and flame radiation. The rich primary zone choice arose as a result of trade-off studies done during early T700 development, whereby starts requiring ease of cold day ignition and acceleration were traded against tendency to smoke. In-as-much as smoke requirements are relatively relaxed for small diameter plumes, the choice of primary zone stoichiometry was favorable for this application. Impact of broad fuel specifications was not a consideration at that time.

All combustor concepts and the baseline design were examined for their performance with Jet A and three NASA ERBS fuel types with respect to:

1. Smoke.
2. Emissions (carbon monoxide, unburned hydrocarbons, and oxides of nitrogen).
3. Flame radiation, and as a consequence shell temperature and cyclic durability.
4. The affect of combustion efficiency and pressure drop on specific fuel consumption
5. Complexity and manufacturability.
6. Reliability and maintainability.
7. Engine weight.

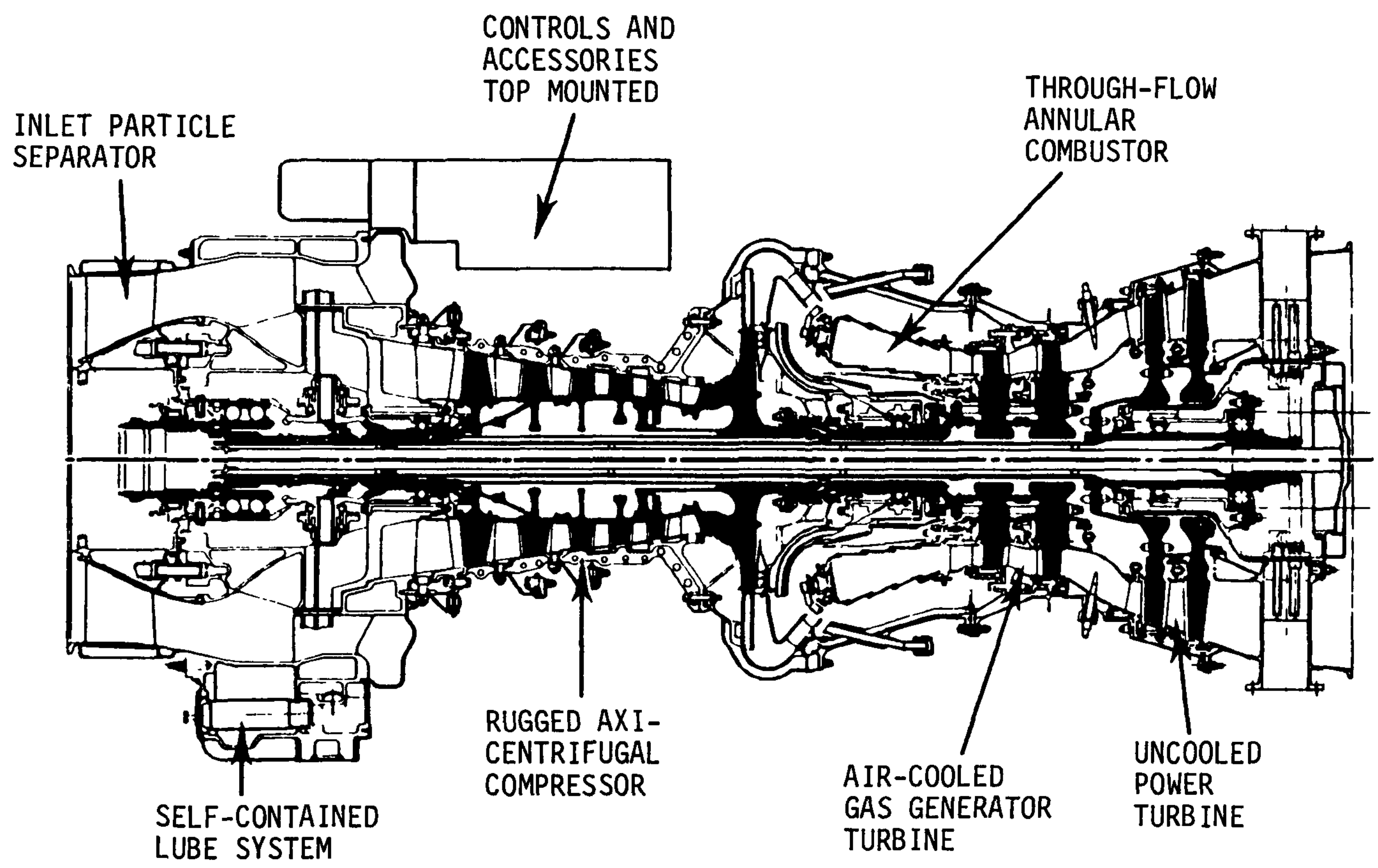

Figure 1. T700 Engine Cross Section.

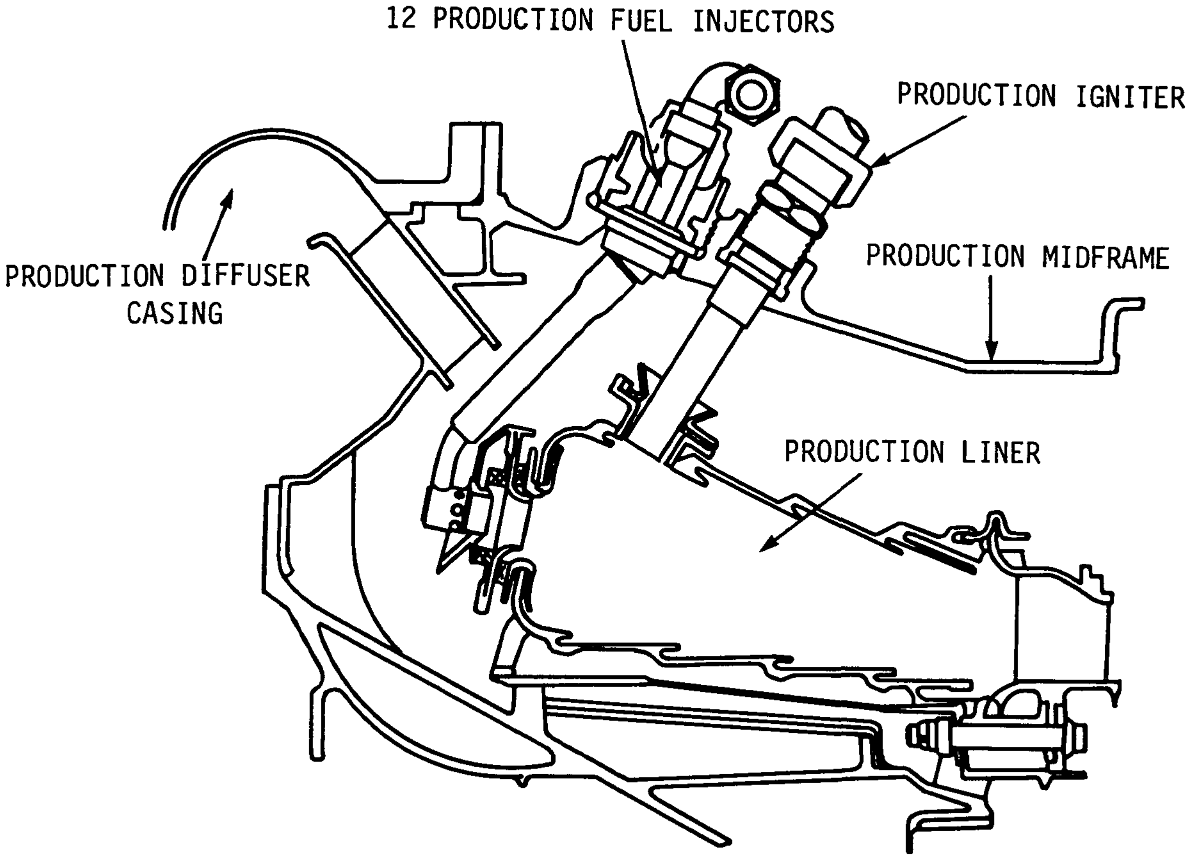

Figure 2. T700-GE-401 and CT7-5 Primerless Combustor.

Results of the study indicated that smoke and flame radiation were primarily affected by changing the fuel specification. As a result, the proposed redesigns were directed at those two problems.

Interestingly, it was concluded that emissions were insignificantly affected. This is due mainly to low emissions levels in the first place. The low levels are a side effect of a number factors that are favorable in this particular cycle and engine size. NOx is limited at high power due to modest pressure ratio (17 instead of 25-30) and very short residence time, due to high aerodynamic loading (space heat release rate is approximately 12 x 10^6 Btu/hr/ft^3/atm). Idle emissions (CO and THC) are low due to high idle pressure ratio (3.8) and a somewhat richer than normal primary equivalence ratio at idle (approximately 0.75 - 0.85 at the dome) which is nearly optimum for high combustion efficiency at idle (approximately 98.2% based on tail pipe gas analysis).

INTRODUCTION

Phase I of this Analytical Fuel Property Effects - Small Combustors program consisted of a purely analytical determination of small engine combustor design concepts that would prepare a representative engine for use with non-standard aviation fuels.

The phase began with selection of a representative production engine, the CT7-5 turboprop which is a commercial derivative of the U.S. Army T700-GE-700 rotorcraft development. The combustor from the CT7-5 is identical to the U.S. Navy T700-GE-401 LAMPS Seahawk version.

A total of eight combustor concepts were then offered to NASA for consideration on their merits as designs which might solve some of the anticipated functional problems associated with burning the ERBS type fuels described by NASA as candidates for future aircraft use. The concepts were responses to the two major problems that were forecast for the baseline T700 combustor; namely, excessive smoke and excessive shell temperature leading to significant reductions in operating life. No additional problems have been forecast.

After NASA selected five combinations of concepts, additional detailed analyses were performed on the five, leading to a narrowing of the field to three preferred designs which have been recommended for Phase II of this program, a test phase.

ERBS FUELS

ERBS fuels as described by NASA are shown in Table 1. They can be described as low hydrogen content, high aromatic content refined petroleum blends similar to the No. 2 distillates. This differs from today's aircraft kerosenes which are No. 1 distillates; for example; Jet A, Jet A1, JP-8, and JP-5.

Density and end point are higher than normal whereas the percent hydrogen and net heat of combustion are lower than normal. The low hydrogen and high aromatics fuels are known from experience to produce high particle content in flames leading to additional smoke and radiant luminosity or heat flux which creates abnormal increases in the operating temperature of the metal walls of the combustor.

It is felt that this effect is a function of hydrogen unsaturation or the existence of double bonds in many of the materials in the petroleum blend. Experience with highly saturated but low hydrogen content materials such as the cruise missile fuel JP-10, has shown deviation from the smoke and heat load levels typical of fuels with 11.8% hydrogen. JP-10 is a pure material with zero aromatics or olefins, but with 11.8% hydrogen; the same as ERBS 11.8, which will have at least 48% aromatics.[1]

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1. Cohen, J.D., and Howell, S., EVALUATION OF JP-9 AND JP-10 FUELS AND THEIR EFFECTS ON TYPICAL TURBOFAN COMBUSTION SYSTEM (Test Hardware was T700-GE-401 Combustor), General Electric Co., Aircraft Engine Business Group, Lynn, MA, 01910, AFWAL Contract No. F33657-78-C-0488, February 26, 1979.

TABLE 1. FUEL SPECIFICATIONS

Specification	ERBS Jet Fuel Value	ERBS 12.3	ERBS 11.8	Jet A
Composition				
Hydrogen, wt %	12.8 ±0.2	12.3 ±0.2	11.8 ±0.2	13.7 typ
Aromatics, vol %	18 min	38 min	48 min	17-20 typ (25 max allowed)
Sulfur, mercaptan, wt %	0.003 max	---	---	0.003 max
Nitrogen, Total, wt %				
Naphthalenes, vol %	13 min	14 min	15 min	---
Hydrocarbon compositional Analysis				
Volatility				
Distillation temperature, °F (°K)				
Initial boiling point	360 (455) max	330 (438) max	300 (422) max	---
10 Percent	300-400 (422-477)	300-400 (422-477)	300-400 (422-477)	400 (477) max
50 Percent	400-500 (477-533)	400-500 (477-533)	400-500 (477-533)	---
90 Percent	500-600 (533-588)	500-600 (533-588)	500-600 (533-588)	---
Final boiling point	650 (616) max	650 (616) max	650 (616) max	572 (573) max
Residue, %				
Loss, %				
Flashpoint, °F (°K)	100 (328) min	100 (328) min	100 (328) min	100 (328) min
Gravity, API 60°F (33°K)				
Gravity, Specific (60/60°F or 306°K)	.841 ±.002	.852 ±.002	.863 ±.002	.775 - .840 (.81 typ)
Fluidity·				
Freezing point, °F (°K)	-10 (250) max	-10 (250) max	-10 (250) max	-40 (233) max
Viscosity @ -10°F (250°K), CS	4 - 12	4 - 12	4 - 12	8.7 typ
Viscosity @ 80°F (300°K), CS	2 - 3	2 - 3	2 - 3	1.9 typ
Combustion				
Net heat of combustion, Btu/lb	18,000-18,300	17,900-18,200	17,700-18,000	18,600 typ
Thermal stability.				
JFTOT, breakpoint temperature, °F (°K)	160 (511) min	460 (511) min	460 (511) min	500 (533) typ
(TDR, 13 max, and P, 0 98 in. 25 mm)				

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.

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.

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 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.

The purpose of this program is to generate newer combustor designs in small engines to minimize or eliminate some of the problems.

Derivation of Nonpetroleum Fuels

Fuel grade hydrocarbons can be derived from sources such as shale, tar sand, and coal which are all 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. Again, this provides significant motivation for this program.

BASELINE PERFORMANCE DISCUSSION

Baseline combustor performance was established to determine what was to be expected from a T700/CT7 type combustor when operating with ERBS type fuels.

SHELL TEMPERATURE STUDIES

A heat transfer routine[2] is utilized in this study, with variable radiant luminosity as a function of hydrogen weight as a percentage of fuel weight. The routine incorporates the effects of convection, radiation, film cooling, and cycle conditions as a function of known flow levels and geometry. The study is parametric in nature and results are shown in their entirety in the Comprehensive Data Report of 15 July 1982.

Figure 3 shows the results on the hottest forward panel to illustrate the predicted effect of high aromatic levels (reduced hydrogen). Increases in shell temperature are predicted to exceed 400°F or roughly 250°K.

This suggests severe life degradation which is shown in Figure 4 plotted against hydrogen weight as a percent of fuel weight. Life ratio was computed from a low-cycle fatigue crack growth strain model normalized against known T700 cyclic life of 15,000 full thermal cycles. In the extreme case of ERBS Fuel 11.8, the life degradation factor drops to 22%, suggesting a reduction in life from 15,000 cycles to 3300 cycles or a loss of 11,700 cycles.

The temperature levels are indeed so high that other failure modes such as blistering and local melt-through may well occur before cracking.

This illustrates the severity of the problem predicted for the baseline system. The problem is addressed in all of the proposed redesigns.

SMOKE AND GASEOUS EMISSIONS

Smoke and emissions levels of the baseline T700/CT7 system are presented in Figures 5 and 6 respectively. As stated previously, smoke is relatively high on an absolute basis, but none-the-less meets military and civil visibility standards with Jet A type fuels.

[2] Cohen, J.D. and Campagnolo, M.L., THIN SHELL STEADY STATE TRANSFER (TSSST), USER MANUAL TM78AEB1167, General Electric Aircraft Engine Business Group, Lynn, MA 01910, June 6, 1978.

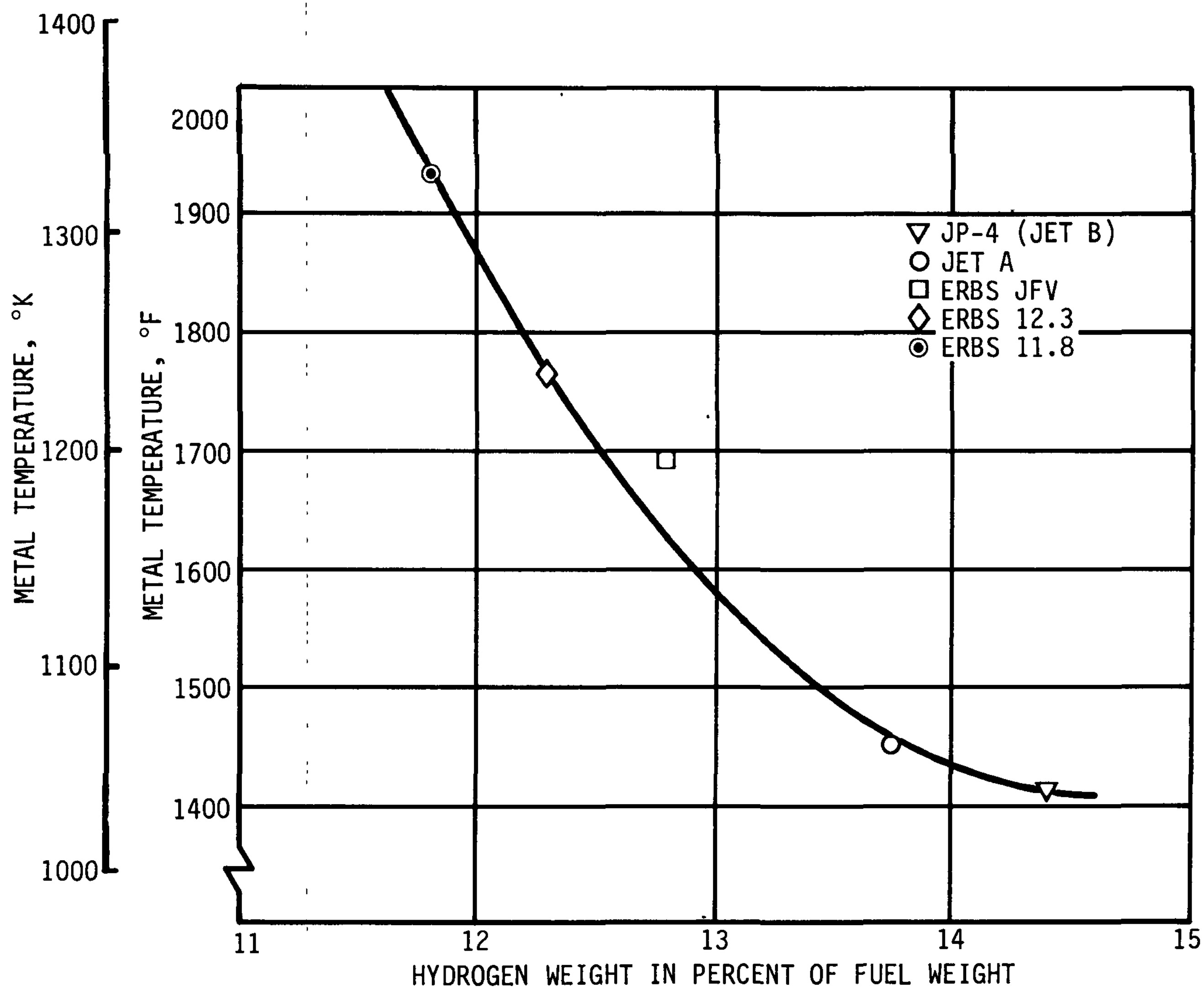

Figure 3. NASA First Panel Metal Temperatures.

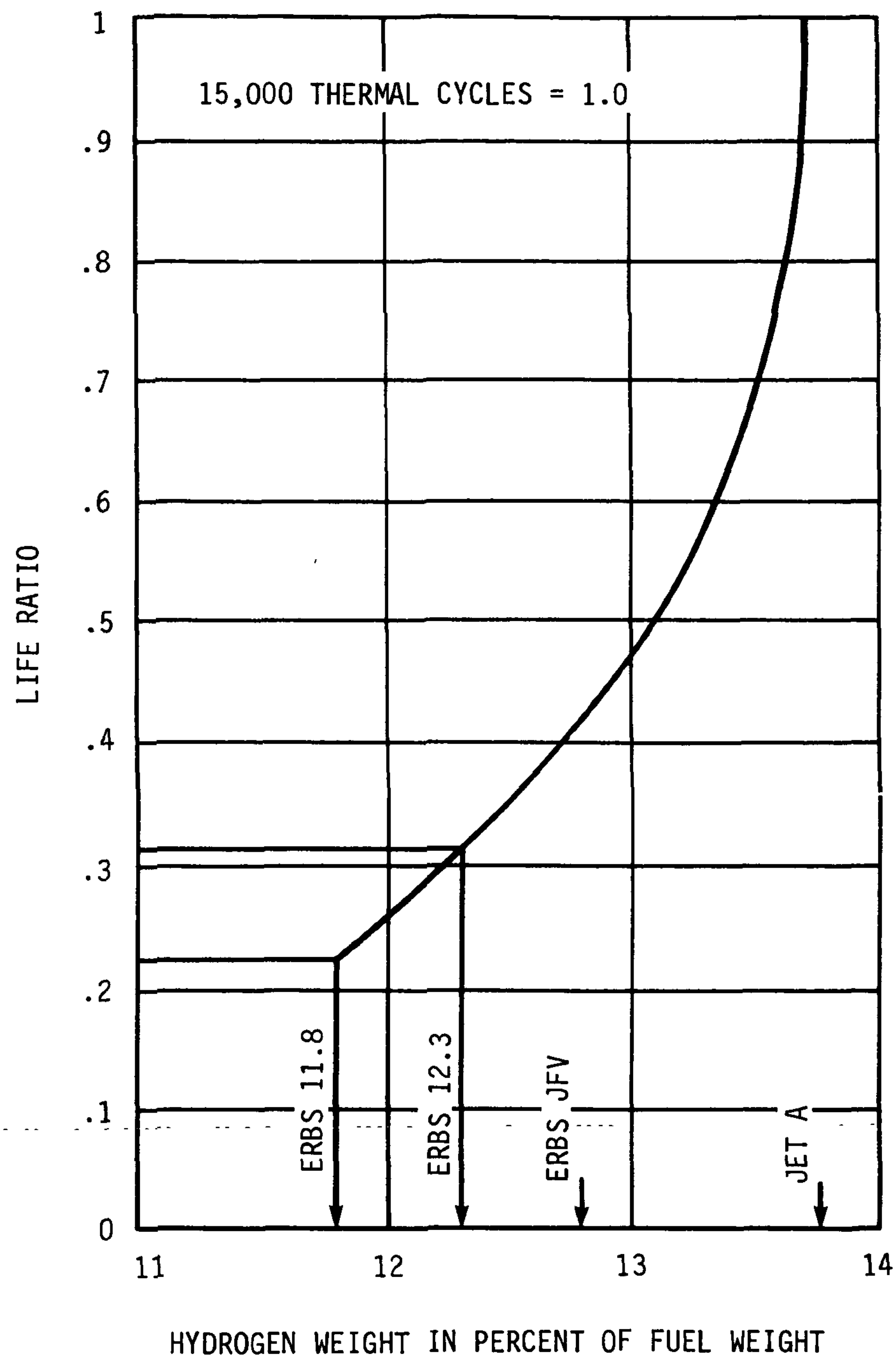

Figure 4. Predicted Life Degradation of Baseline Combustor as a Function of Fuel Properties.

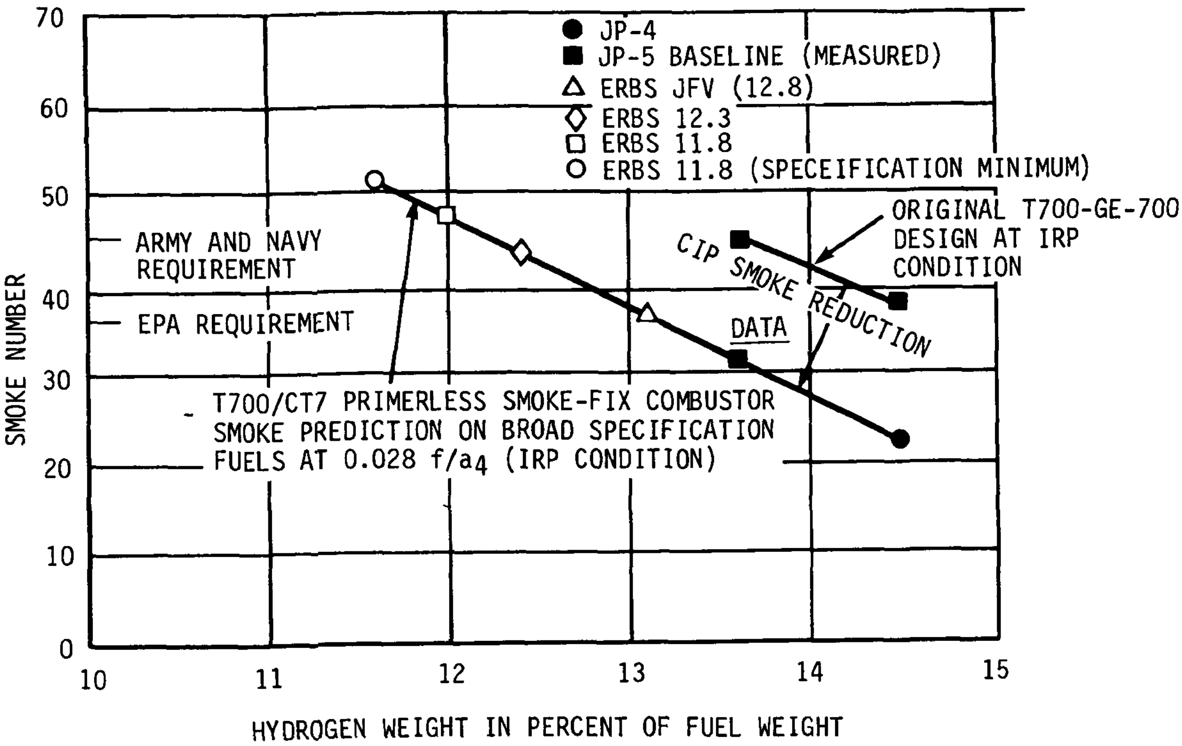

Figure 5. T700/CT7 Engine Smoke Fix Characteristics.

Smoke Characteristics at Full Rated Power

Figure 5 demonstrates rising smoke levels predicted for lower hydrogen content fuels. Smoke number definition is consistent with SAE ARP 1179. Smoke numbers are predicted to be unacceptable for civil aviation with all of the ERBS type fuels.

Gaseous Exhaust Emissions

An exhaust emissions survey for the T700 engine is presented in Figure 6. The survey was performed in accordance with SAE ARP 1256. It was performed with both JP-4 and JP-5 fuels, and it is noted that the results were very nearly the same for both fuel types. The carbon monoxide and hydrocarbon emissions can be converted to combustion efficiency in the idle to full power range and when combined with far off design stability data from two previous programs[1], results in the curve shown in Figure 7, where combustion efficiency is displayed as a function of the Longwell loading parameter[3].

[3] Longwell, J.P., and Weiss, M.A. HEAT RELEASE RATES IN HYDROCARBON COMBINATIONS, PROCEEDINGS OF THE JOINT CONFERENCE OR COMBUSTIONS, ASME and the (British) Institute of Mechanical Engineering, P9, June 1955.

EXHAUST EMISSIONS SURVEY - 9/24/76 AND 9/27/76
SCOTT LABORATORY ANALYSIS

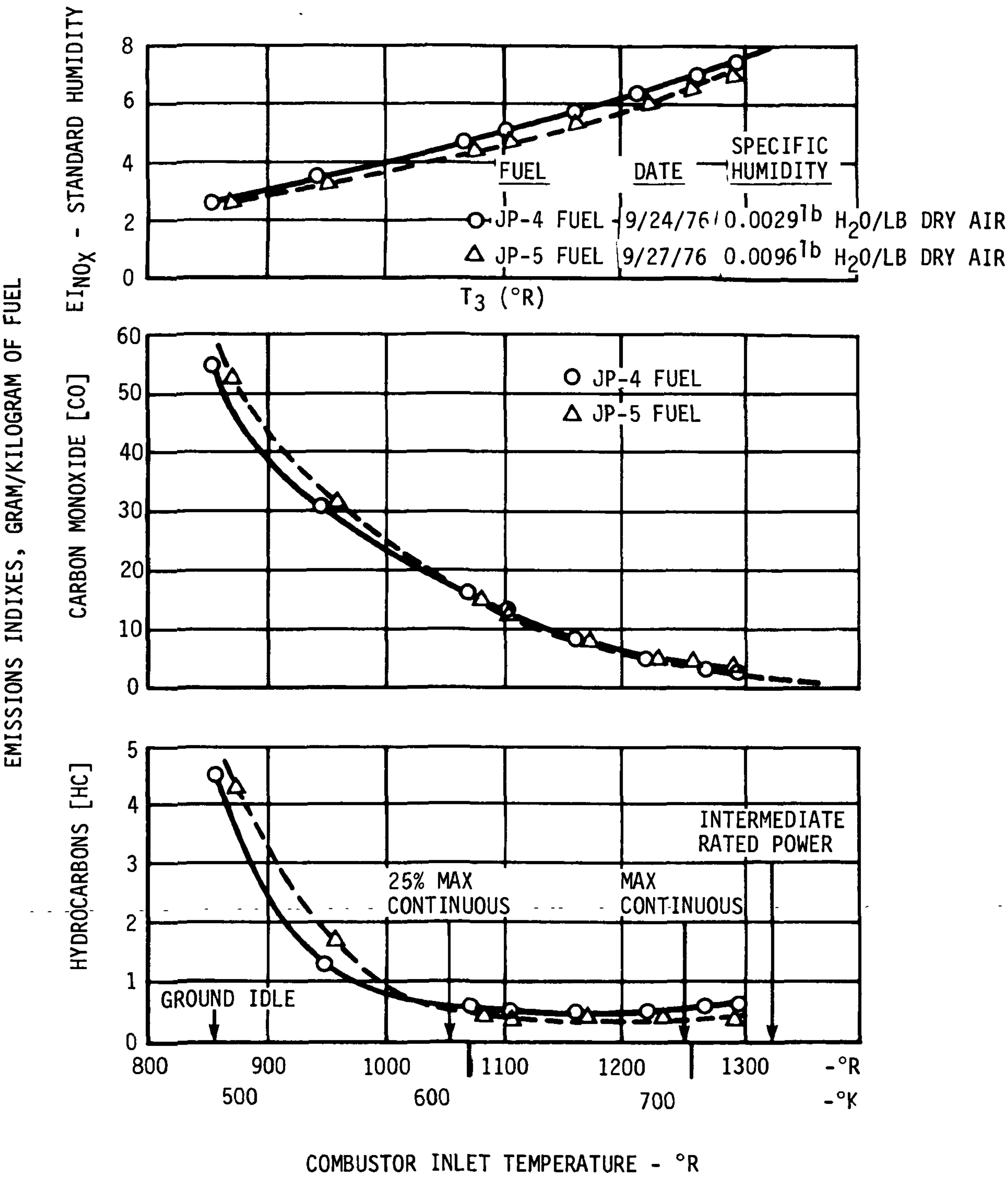

Figure 6. Exhaust Emission Measurements - T700-GE-700 Engine Serial No. 207010-5B.

At Sea level static, the lowest operating combustion efficiency is 98.27%, measured at ground idle. At full power, the measurement corresponds to 99.86%.

ERBS fuels are not expected to have a significant effect on either emissions or combustion efficiency on this system. Kinetic calculations show that flame temperature increases are expected with lower hydrogen content, but are too slight to significantly affect emissions.

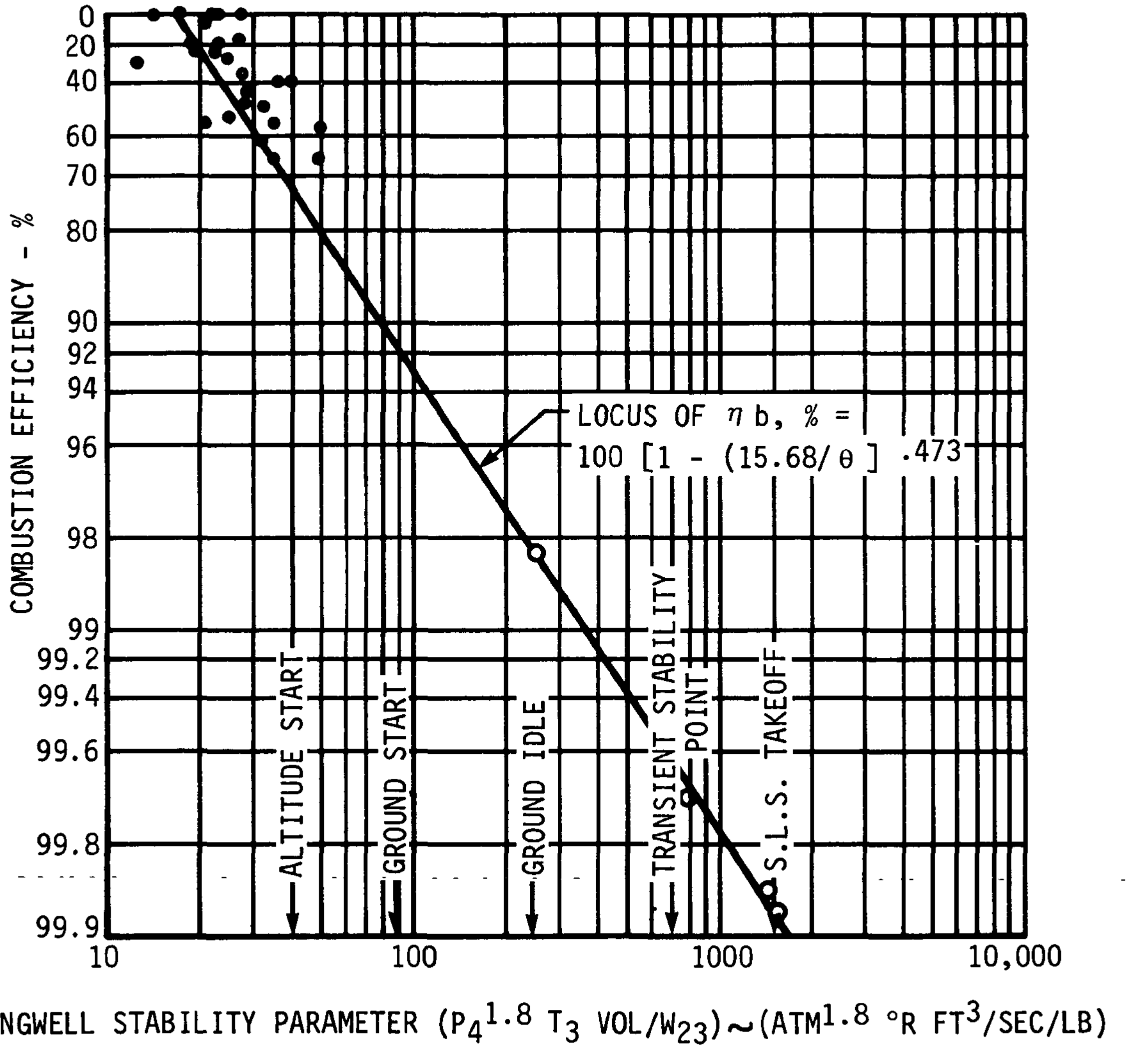

Figure 7. CT7-5 Combustor Efficiency Correlation.

RECOMMENDED DESIGNS

Five designs were defined by NASA out of an original field of eight concepts. The full description of the original eight is provided in the Comprehensive Data Report for this program dated 15 July 82. The following Design Descriptions include the selection ratings and preliminary General Electric Recommendations for the three designs proposed.

DESIGN DESCRIPTIONS

The order of the designs described in this paragraph does not indicate a preference. Designs are labeled A, B and C.

DESIGN A

Design A has a lean dome with sector burning combined with reverse flow convectors including an aft impingement stage (see Figure 8).

Smoke reduction is achieved on this design by increasing primary zone air flow through the forward shells. Ignition and flameout margin is maintained (or improved) by use of sector burning if necessary. This is achieved, by restricting the number of active fuel injectors during low fuel flow operation. Such techniques increase local fuel air ratio to provide ignition margin. This type of behavior can also be induced in the low-pressure fuel injectors by elimination of head effect restrictions allowing a lopsided fuel distribution at minimum flow. This provides a higher-than-average fuel air distribution in the lower half of the combustor.

Reverse flow convectors on the panels of the combustor combine an impingement stage at the hottest axial position on the panel with convective axial flow forward in the cooler positions. This management has due potential capability of minimizing the axial temperature gradient that is normally present in film cooled designed.

DESIGN B

Design B has dilution flow with impingement cooled shells and advanced air blast injectors. (see Figures 9 and 10).

Flexible impingement shields will be assembled to the inner and outer shells of the T700 combustor. All of the shell flow (both dilution and film) will pass initially through the impingement shield hole patterns providing enhanced convective cooling. Since liner pressure drop is now shared between the impingement shield and the combustor shells, all of the holes in the combustor must be increased by 19% in overall diameter to maintain pressure drop and air flow distribution.

The advanced air blast injectors add more air through the care of the swirlers affecting spray inducing forces and leaning out the primary swirler. Such an approach has been shown to affect smoke favorably, provided fuel distribution is not negatively affected.

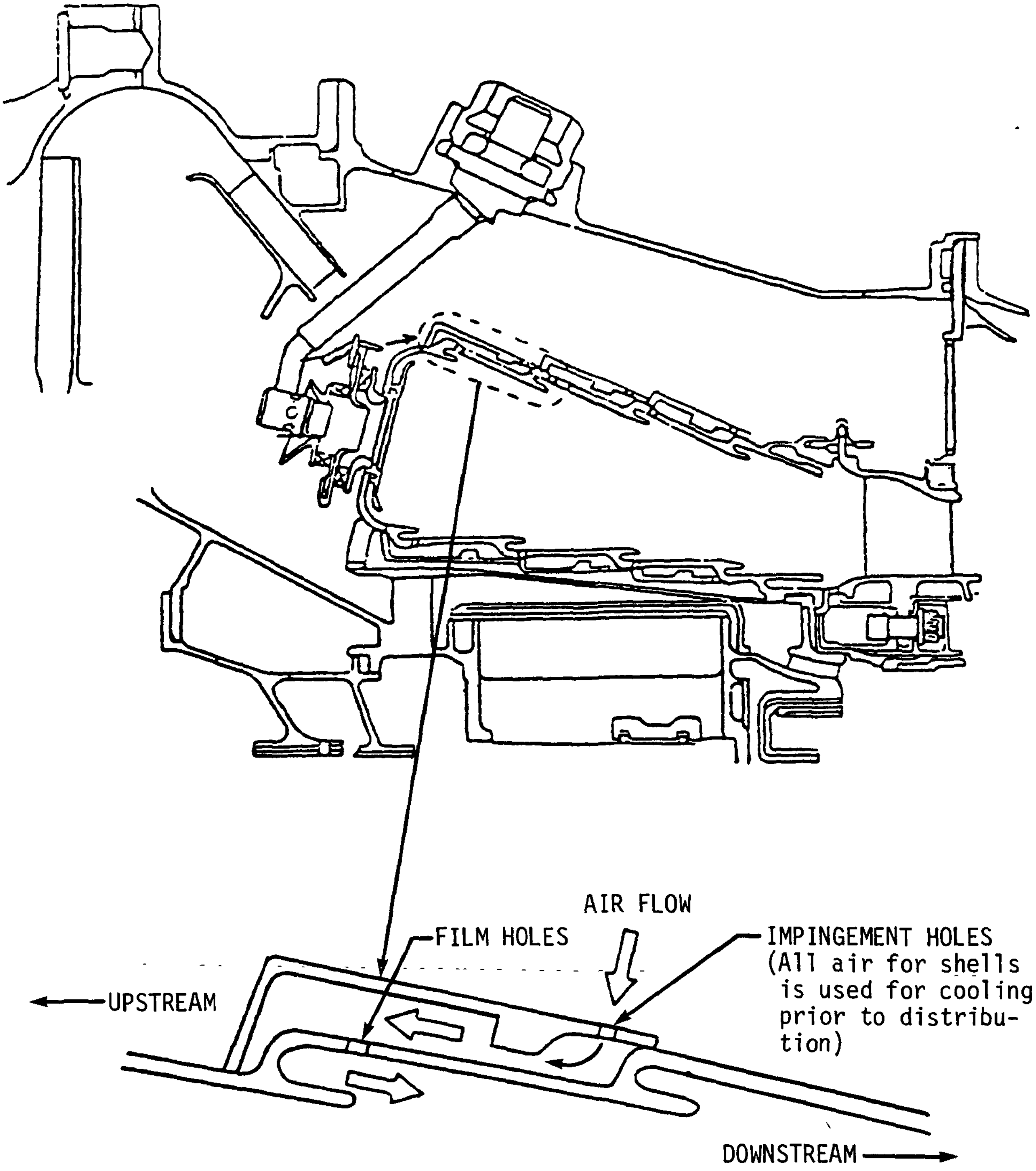

Figure 8. Reverse Flow Convectors with Impingement Stage - Design A.

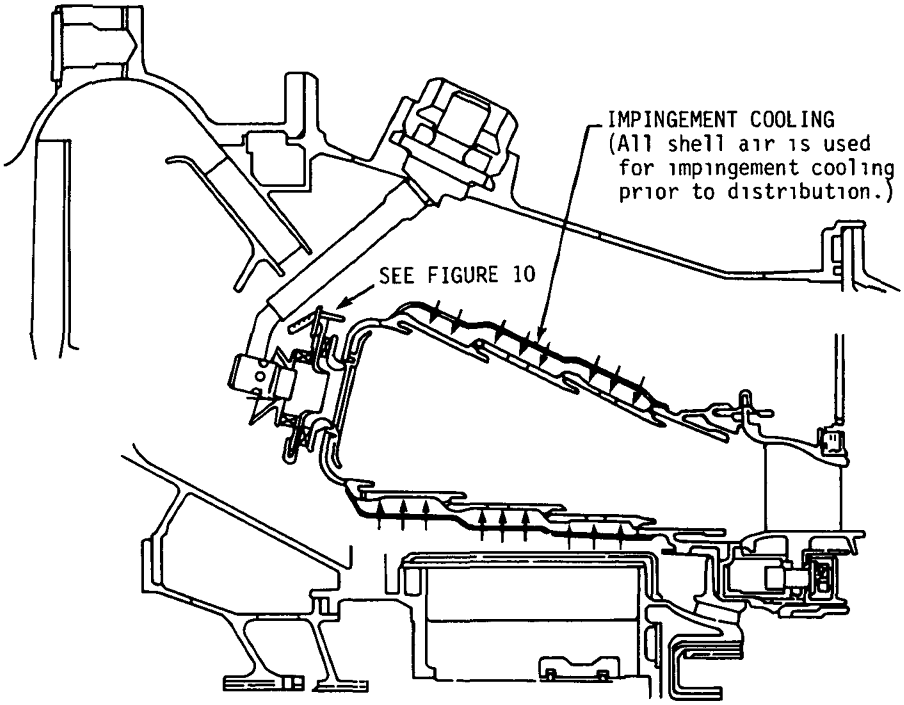

Figure 9. 100% Impingement Cooled Shells - Design B.

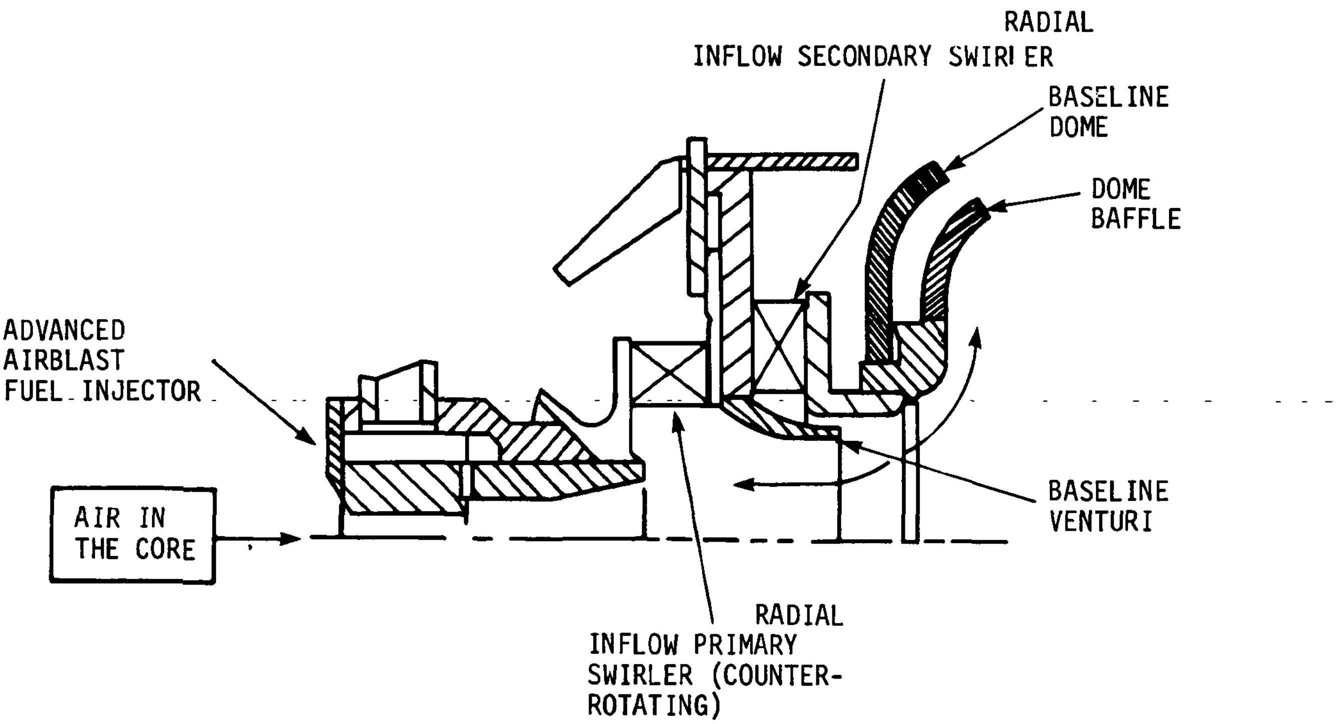

Figure 10. Advanced Air Blast Fuel Injectors - Design B.

DESIGN C

Design C has impingement cooled replaceable shields with simulated variable geometry swirlers. (see Figures 11 and 12).

The replaceable shield concept is considered to be an advanced structural design which provides all the impingement cooling advantages of Design B plus mechanical features for long structural life. This is a variation of the shingled-liner concept, wherein the outer impingement shield provides the structural "backbone" of the design and the hot gas facing shields are nonstructural in function.

The variable geometry aspect will be a demonstration of the potential advantages of variable flow secondary swirler inlets. The variable geometry actuation will not be set in place and is considered to be beyond the scope of this program. Actuation will be performed by manual settings.

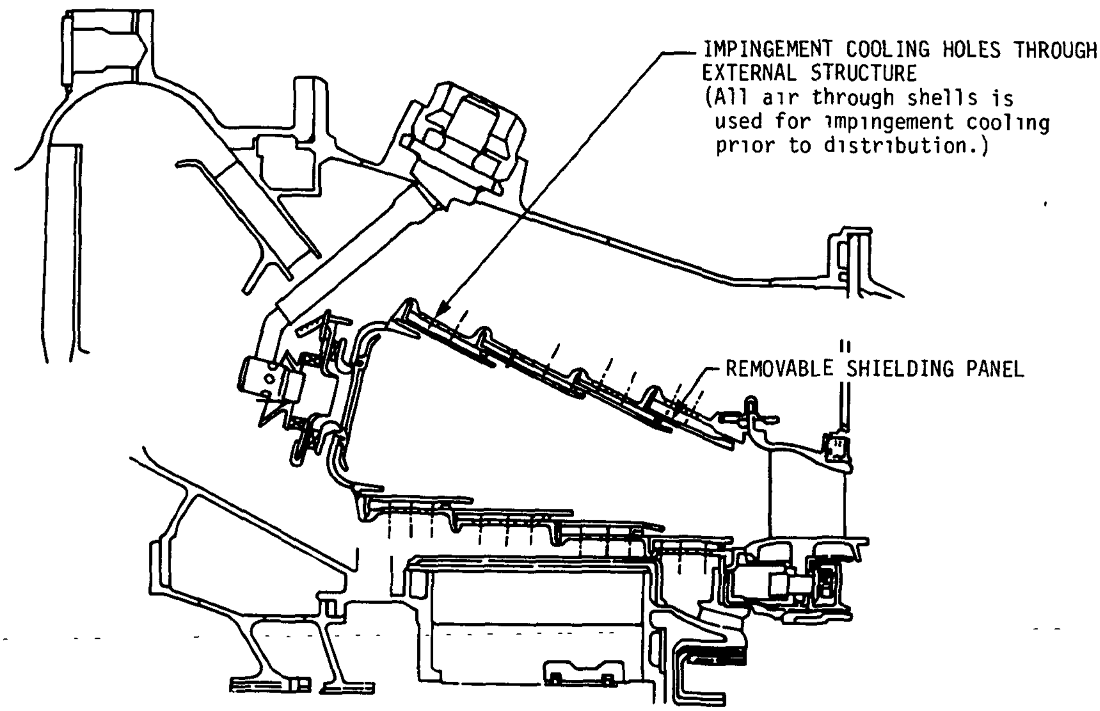

Figure 11. 100% Impingement Cooled with Replaceable Flame Shields - Design C.

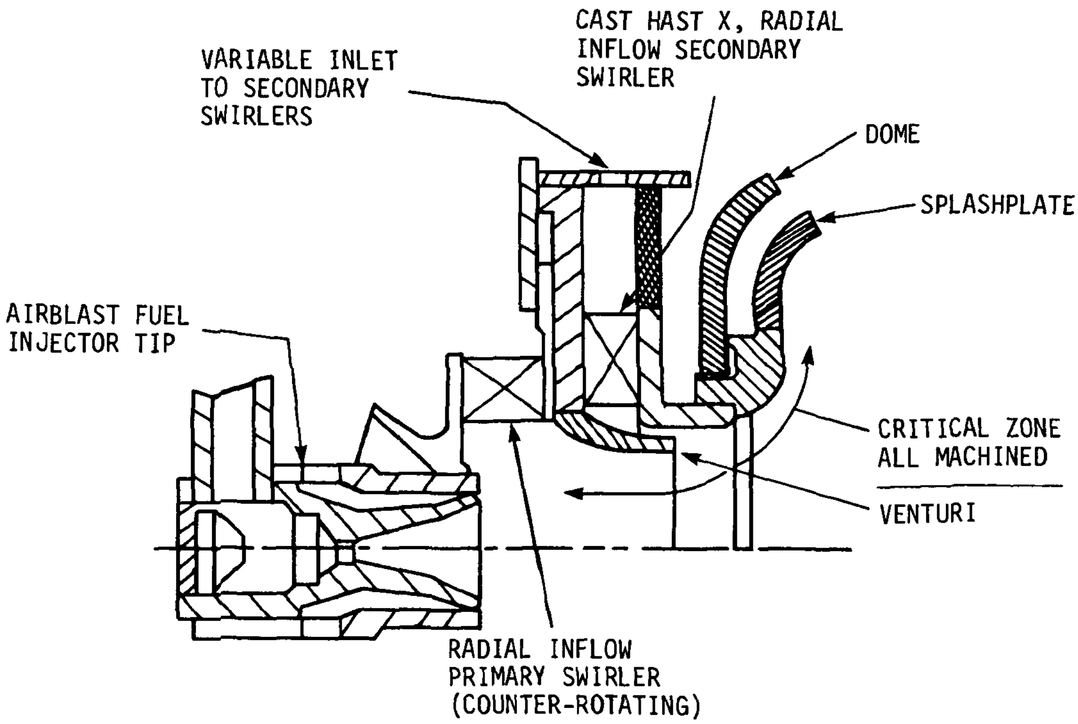

Figure 12. Variable Geometry Swirlers - Design C.

DESIGN ANALYSES

The three redesigns described above have been compared with the baseline combustor in several different ways as described in the following paragraphs.

The analyses have been designed to emphasize the impacts, if any, of the following fuel properties:

1. Hydrogen content (and aromaticity).
2. Viscosity.
3. Volatility.
4. Thermal Stability.

FUEL PROPERTY PERFORMANCE-RELATED LIMITATIONS

These fuel properties can be related to a number of performance related limitations to the operation of the T700 engine.

Maximum Allowable Fuel Temperature to the Engine Fuel Manifold Inlet

On the T700 engine, bearing frictional losses picked up by the lube system are rejected as heat to the incoming fuel. Current specifications allow a maximum fuel temperature of 300°F (422°K) with military fuels and Jet A. JFTOT temperatures with typical kerosene type fuels run from 490°F (527°K). As hydrogen percentage drops to about 12.8, the thermal stability JFTOT temperatures decay to less than 470°F (460°F or 511°K minimum is given for ERBS requirements).

It has been shown in previous programs that allowable running temperature can be based on a constant difference from JFTOT to minimize fuel nozzle fouling. For this reason, it is recommended that maximum allowable running temperature be reduced by 30°F (17°K) to 270°F (405°K) for ERBS fuel use.

Fuel Injector Type and its Fuel Flow Rate versus Pressure Drop

The T700 uses air blast atomizers. Fuel nozzle pressure is used only for metering and distribution accuracy. Atomization and spray trajectory are not issues that are controlled by the design schedule or fuel viscosity, consequently fuel properties are not expected to have any effect on the pressure schedule requirement. Any shift in the schedule due to density variation upward is totally compensated for by heating value reduction, hence, no compensation of any type will be necessary in the fuel delivery system.

Diffuser Total Pressure Loss

The compressor diffuser and aerodynamic properties are neither affected by ERBS fuels nor will the design be altered to accommodate any significant changes. The dump loss (approximately 0.5%) is taken prior to split up of the primary and secondary streams.

Primary Zone Airflow, Fuel Flow, and Equivalence Ratio

Designs A, B, and C are required to have reduced primary zone equivalence ratio for smoke reduction with fuels of high aromaticity. Since aromaticity and hydrogen percentage can be shown to be the inverse of one another in practical blends of light fuel grade hydrocarbons, the smoke number predictions are based on hydrogen content rather than aromaticity.

Figure 13 shows the effect of swirler equivalence ratio on smoke based on T700-GE-401 measurements and the indicated effect of fuel type. Figure 14 relates hydrogen percentage to aromaticity.

Designs A, B, and C will be adjusted to meet the indicated cup equivalence ratio of 2.24 at full sea level rated power.

Liner Cooling Structure and Airflow Rate and Maximum Liner Temperature

Designs A, B, and C employ double-walled structures for use of enhanced convective cooling by means of impingement schemes and/or impingement combined with accelerated velocity schemes. This is intended to counter-act the effects of higher flame radiation expected from fuels of high aromaticity and to suppress the variability expected from fuels of widely varying properties.

Parametric Heat Transfer Analysis

The impact of enhanced convective cooling has been studied through the use of a detailed one dimensional, steady-state, heat transfer routine for all the fuels of concern to the contractor. The routine displays isotherm plots for practical ranges of convective cooling coefficient and film cooling effectiveness. The T700 geometry and cooling stream flows are implied and radiant heat load of each fuel of interest is implied.

The forward three panels (out of four) have been studied on both inner and outer shell for JP-4 (Jet B), Jet A, and each of the three ERBS fuels.

Panel four has been excluded as irrelevant to the study, since it is already impingement cooled and since it is not exposed to a significant radiational heat source.

Figures 15 and 16 condense all of the results into an impact study of the effect of hydrogen percentage on panel temperature for design concepts B and C.

As can be seen, Panel 1 in all cases is the hottest followed by Panels 2 and 3 respectively. The highest temperatures are predicted for ERBS 11.8 and are below 1500°F (1089°K) for the worse case of 11.6% hydrogen content. This is well within the capability of Hastelloy X suggesting a successful predicted result for the impingement cooled schemes.

These plots are an indication of what enhanced convective cooling is capable of.

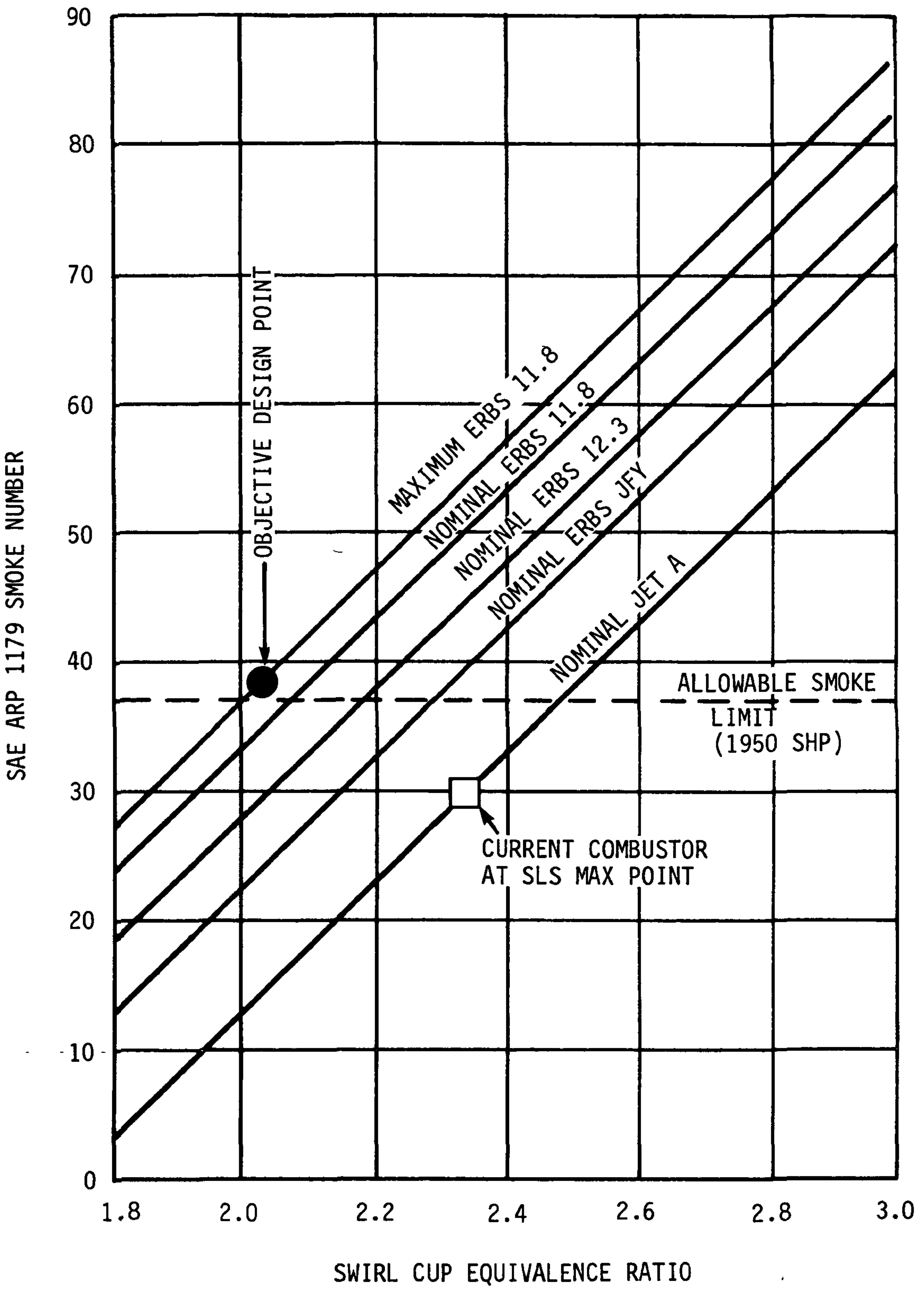

Figure 13. Effect of Swirl Cup and Equivalence Ratio and Fuel Type (Hydrogen %) on Smoke.

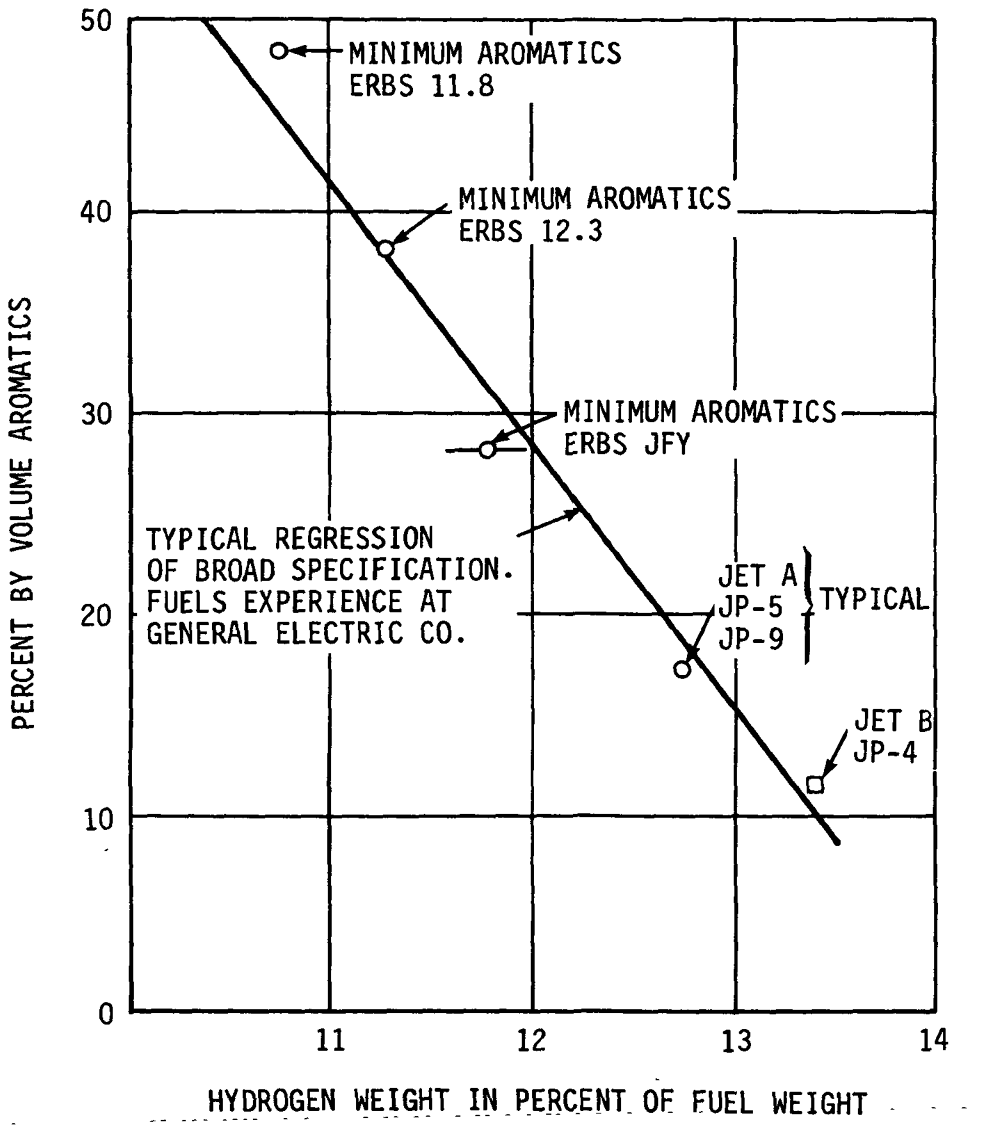

Figure 14. Relationship of Hydrogen Content and Aromaticity.

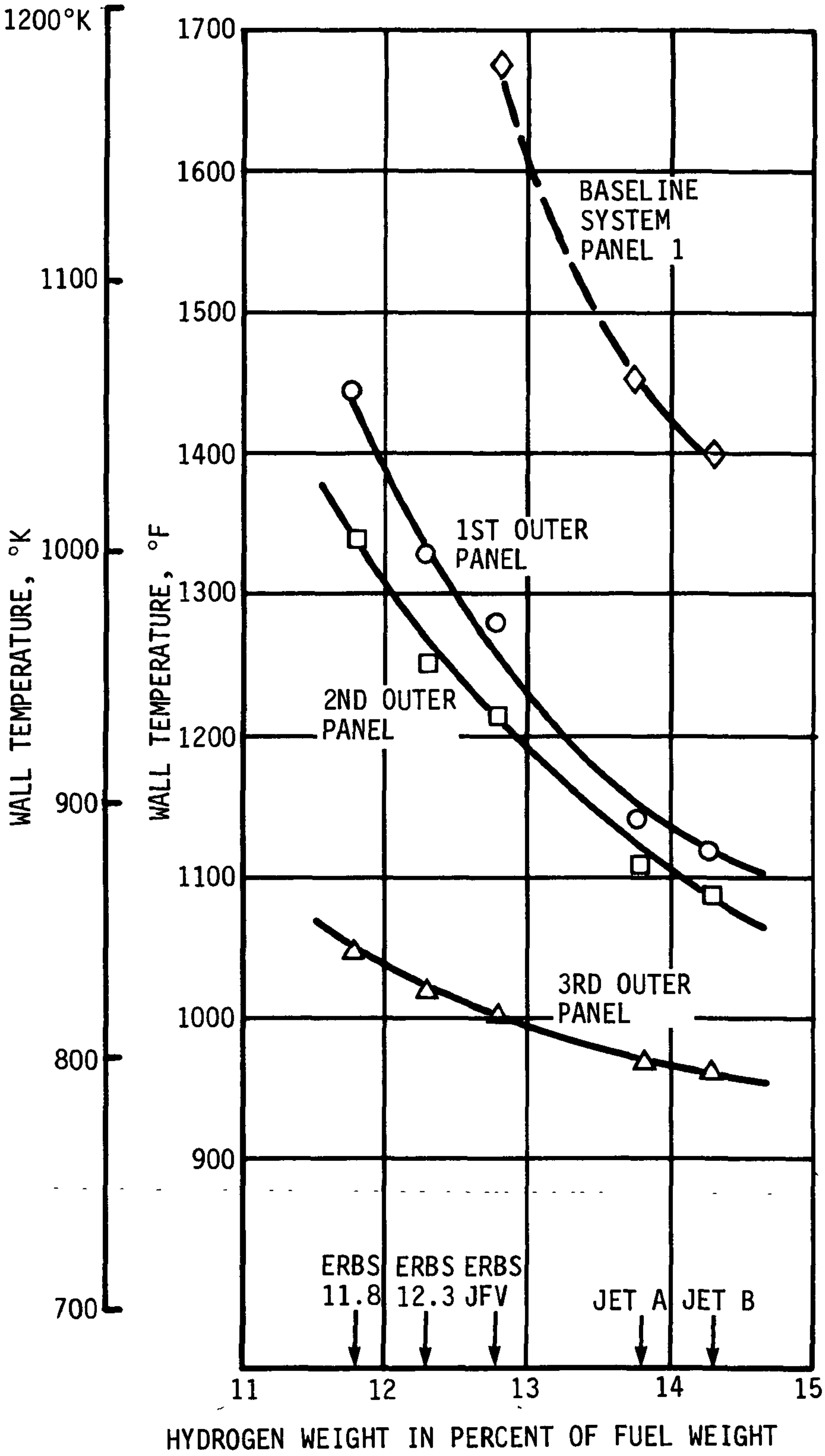

Figure 15. Effect of Fuel Properties on Predicted Maximum Outer Panel Temperatures for Design Concepts B and C.

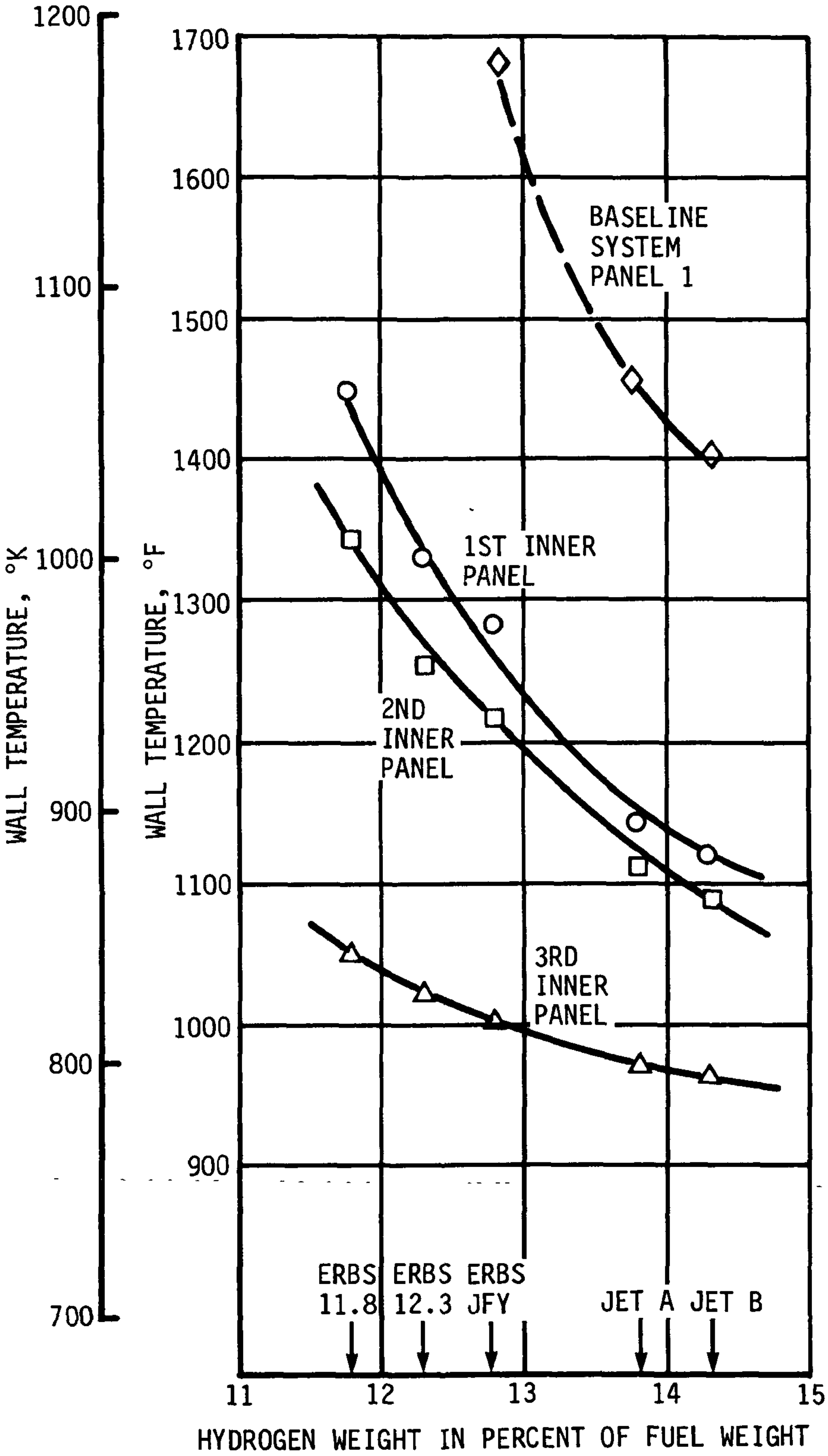

Figure 16. Effect of Fuel Properties on Predicted Maximum Inner Panel Temperatures for Design Concepts B and C.

Dilution Airflow Rate

The previous cooling analysis assumes constant cooling flow at present levels. Therefore, dilution airflow is not expected to change significantly. A small reduction is comtemplated in Designs A, B, and C to provide the leaner primary zone contemplated in those cases. This involves a shift of only 1.82% of the total combustor air flow corresponding to a 5% reduction to dilution air.

Changes of this magnitude are generally not of concern, especially if done in selective circumferential locations.

If this creates a problem, it is possible to compensate by a reduction in cooling film flow which always proves to be beneficial if there is shell temperature margin. Significant margin is predicted. Therefore, reduced total cooling is another variable to consider in detailed design. This will, of course, increase dilution flow and help reduce pattern factor.

Combustor Liner Airflow Distribution

The following changes are contemplated in airflow distribution in the combustor if no major changes of cooling flow are selected.

	Baseline	Designs A, B, and C
Swirlers	16.4%	18.22%
Dome Plate Cooling	9.6%	9.6%
Film Cooling	32.0%	32.0% - 30.18%
Turbine Band Cooling	4.0%	4.0%
Seal Leakage	1.0%	1.0%
Dilution	37.0%	35.18% - 37.0%

Because the heat transfer analysis indicated such low temperature it may be possible to lower total shell cooling flow and increase dilution correspondingly by 2-5%. These numbers need more study. No change is anticipated in dome cooling at this time.

In the case of the baseline system, dome cooling and turbine band cooling are used for combustor impingement cooling purposes. In designs A, B, and C the film cooling and dilution are used initially for impingement and enchanced convective cooling purposes.

As can be seen from the braakdown, very little internal flow is significantly changed.

Configuration C has the potential of increasing dome flow even more because of variable geometry. The converse of dome flow reduction during start and idle operation will also be accomplished.

Combustor Liner and System Total Pressure Loss

No changes are contemplated except for the variable geometry swirler case.

Closed actuation of the variable geometry (VG) will raise pressure drop during start and possibly through idle. At power settings the VG will be fully open keeping pressure drop at baseline levels so as not to affect SFC.

Maximum Combustion Liner Temperature

The baseline combustor is not subjected to temperatures higher than 1500°F (1089°K) with Jet A. The predicted effects on designs B and C do not exceed this value even with the worst ERBS 11.8 at 11.6% hydrogen.

DESIGN A ANALYSIS

A separate analysis was performed on design A to detail the character of the reverse flow convector idea, and to assure that its temperature with ERBS 11.8 did not exceed the baseline with Jet A.

This design was compared in detail to the baseline combustor. The reverse flow convector concept was considered risky (until this study was complete) due to the uniquely different convective distribution. The results of the study suggest a surprisingly uniform axial temperature distribution and low temperature levels even with ERBS 11.8.

A TSSST[3] Analysis of reverse flow convectors with an impingement stage, results in low predicted wall temperatures for NASA broad specification fuels.

The predicted wall temperature for each of the first three outer and inner panels of the T700 was determined for an impingement stage with reverse flow convectors using TSSST. Table 2 is a listing of the predicted wall temperatures at the above locations for JP-4 and JP-5, ERBS 12.8, ERBS 12.3, and ERBS 11.8.

In summary, the predictions suggest that this concept will meet the original intent of providing enhanced cooling with lower axial gradients.

For the first panel, the maximum predicted wall temperature is located at the slot discharge, and the temperature decreases as you proceed down the panel. The largest temperature drop across the panel is 120°F (67.7°K). The second panel has approximately the same temperature at the slot discharge and at the midpoint with the coolest temperature located at the end of the panel. The third panel exhibits the same temperature (within 10°F or 5.6°K) along its entire length.

The temperature predicted at the midpoint of each panel is the worst case since this analysis does not consider the area constriction in the reverse flow convector. This decrease in area will result in high velocities and thus, larger cooling coefficients and lower wall temperatures.

3. Ibid pg 10.

TABLE 2. WALL TEMPERATURE

Fuel	Panel	Slot Discharge °F	Slot Discharge (°K)	Middle Point °F	Middle Point (°K)	End of Panel °F	End of Panel (°K)
JP-4	1st	941.7	(788.6)	940.0	(777.6)	902.3	(756.7)
JP-5	Outer	954.5	(785.7)	951.2	(783.8)	908.9	(760.3)
ERBS 12.8		1024.7	(824.7)	1012.7	(818.0)	945.6	(780.7)
ERBS 12.3		1048.8	(838.1)	1034.1	(829.9)	958.3	(787.8)
ERBS 11.8		1111.3	(872.8)	1089.2	(860.5)	991.3	(806.1)
JP-4	1st	924.1	(768.8)	923.3	(768.3)	890.6	(750.2)
JP-5	Inner	934.8	(774.7)	932.6	(773.5)	894.9	(752.6)
ERBS 12.8		993.7	(807.4)	983.6	(801.8)	916.4	(764.5)
ERBS 12.3		1014.3	(818.9)	1001.2	(811.6)	923.3	(768.3)
ERBS 11.8		1067.0	(848.2)	1046.9	(837.0)	961.4	(789.5)
JP-4	2nd	919.3	(766.1)	926.8	(770.3)	896.6	(753.5)
JP-5	Outer	929.6	(771.8)	935.6	(775.2)	901.7	(756.3)
ERBS 12.8		985.8	(803.1)	984.1	(802.1)	929.7	(771.9)
ERBS 12.3		1005.3	(813.9)	1000.9	(811.4)	939.5	(777.3)
ERBS 11.8		1055.9	(842.0)	1044.7	(835.8)	964.9	(791.4)
JP-4	2nd	881.3	(745.0)	885.0	(742.1)	869.0	(738.2)
JP-5	Inner	887.1	(748.2)	891.1	(750.4)	871.4	(739.5)
ERBS 12.8		919.1	(766.0)	918.8	(765.8)	883.2	(746.1)
ERBS 12.3		930.2	(772.2)	928.5	(771.2)	886.9	(748.1)
ERBS 11.8		959.3	(788.3)	953.7	(785.2)	908.0	(759.8)
JP-4	3rd	851.5	(728.4)	860.6	(733.5)	854.5	(730.1)
JP-5	Outer	853.8	(729.7)	862.6	(734.6)	855.7	(730.8)
ERBS 12.8		866.5	(736.8)	873.6	(740.7)	862.1	(734.3)
ERBS 12.3		870.9	(739.2)	877.5	(742.9)	864.3	(735.6)
ERBS 11.8		882.2	(745.5)	887.4	(748.4)	865.5	(736.2)
JP-4	3rd	847.4	(726.2)	853.8	(729.7)	849.0	(727.1)
JP-5	Inner	849.2	(727.2)	855.3	(730.6)	849.7	(727.4)
ERBS 12.8		856.3	(731.1)	864.1	(735.4)	853.5	(729.6)
ERBS 12.3		862.8	(734.7)	863.6	(735.2)	855.0	(730.4)
ERBS 11.8		871.8	(739.7)	869.7	(738.6)	857.3	(731.7)

Figures 17 and 18 show the temperature distribution superimposed on a side view of the T700 for both JP-4 fuel and ERBS 11.8, respectively. Figure 16 illustrates the existing T700 temperature distribution with the galues of ERBS 11.8 (worst case) for the reverse flow impingement concept. As shown, even a low percent hydrogen fuel will give temperatures lower than the existing temperatures when the reverse flow with impingement concept is implemented.

CONCLUSIONS

Reverse flow convectors with impingement is a very effective cooling concept. It possesses a lower wall temperature distribution than the exisitng T700 temperature distribution even with ERBS 11.8.

Smoke

The following table describes anticipated exhaust smoke levels (SAE ARP 1179A).

Fuel	Baseline	Combustor Designs A, B, C
Jet A	30	15
ERBS 11.8	52	37

and is based on Figure 13 which corresponds to rated power operation.

Exhaust Emissions and Combustion Efficiency

No significant change is anticipated between the baseline and designs A, B, and C, nor is any fuel effect expected.

Life

Designs A, B, and C are all expected to have fatigue lives in excess of 15,000 thermal cycles, when operated with ERBS 11.8.

Reliability and Maintainability

On the basis of similarity and life predictions, reliability is expected to be similar for all designs. Maintainability in terms of assembly and removal of combustor hardware is expected to be similar, however, all of the proposed designs will be more difficult and costly to repair due to the double walled construction.

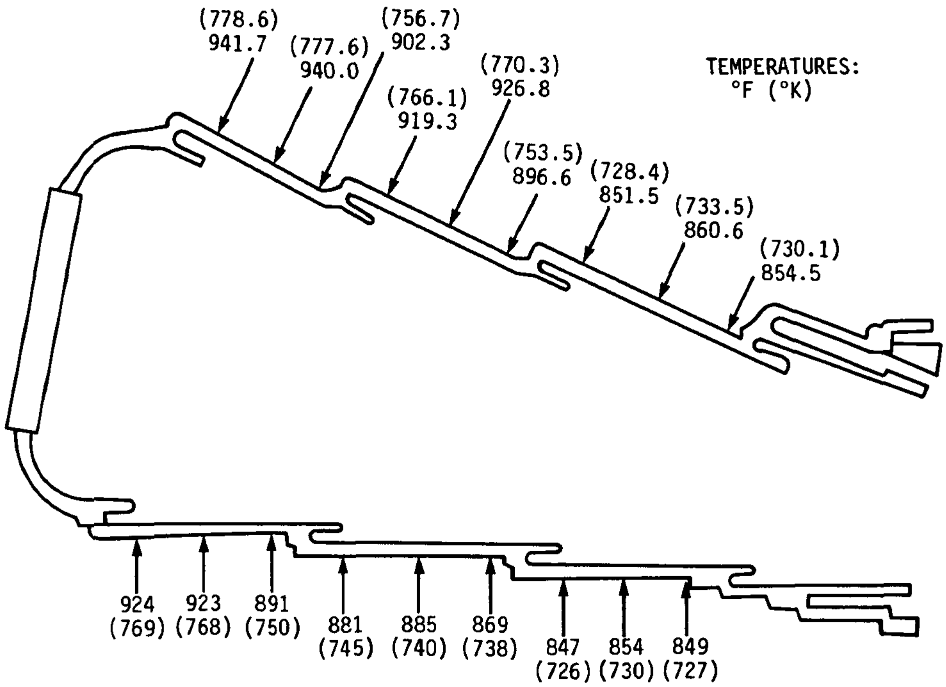

Figure 17. T700 Temperature Distribtuion for the Reverse Flow Concept with Impingement Using JP-4.

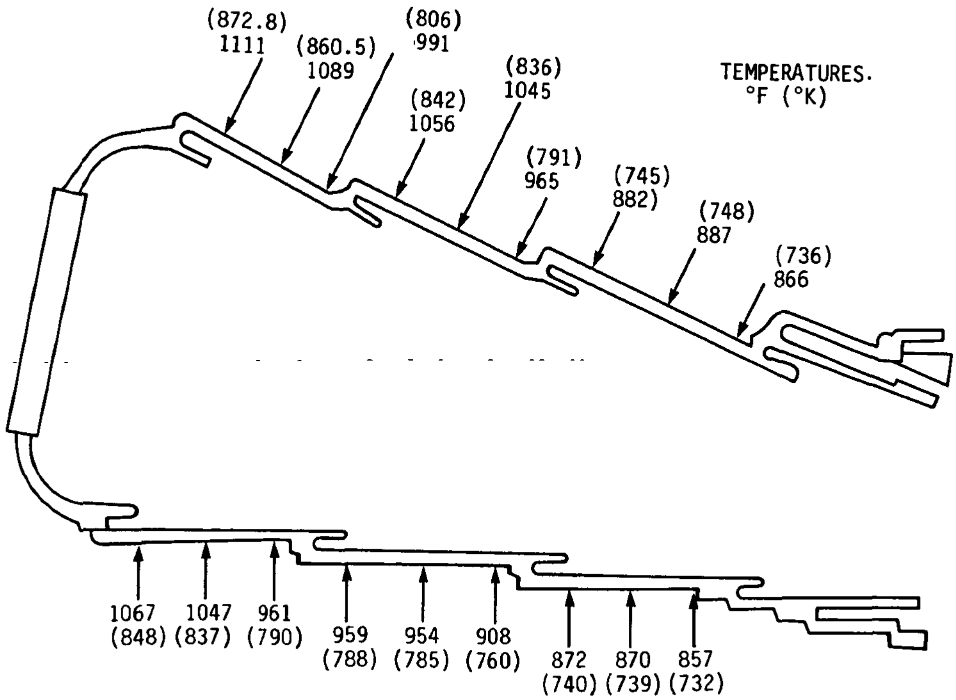

Figure 18. T700 Temperature Distribution for the Reverse Flow Concept with Impingement Using ERBS 11.8 °F (°K).

Weight

The following engine weight increases are expected to the present 430 lb(195 kg) engine.

Design	A	+ 2.0 lb (0.91 kg)
	B	+ 1.7 lb (0.77 kg)
	C	+ 3.5 - 4.0 lb (1.59 - 1.81 kg)

Effect on Engine SFC and Mission

There will be no effect on a corrected SFC basis. The uncorrected SFC will increase purely on the basis of inverse net heating value ratio.

The airframe will be slightly heavier at full load takeoff, if tanks are filled, due to greater fuel density. A slight range increase is possible, in the vicinity of 2% if fuel tanks are filled to maximum volume. Depending on airframe and mission total payload may have to be reduced slightly to compensate for a 6.5% maximum increase in fuel weight.