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The NASA Broad-Specification Fuels Combustion Technology Program—An Assessment of Phase I Test Results

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THE NASA BROAD-SPECIFICATION FUELS COMBUSTION TECHNOLOGY PROGRAM
- AN ASSESSMENT OF PHASE I TEST RESULTS

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ABSTRACT

An assessment is made of the results of Phase I screening testing of current and advanced combustion system concepts using several broadened-properties fuels. The severity of each of several fuels-properties effects on combustor performance or liner life is discussed, as well as design techniques with the potential to offset these adverse effects. The selection of concepts to be pursued in Phase II refinement testing is described. This selection takes into account the relative costs and complexities of the concepts, the current outlook on pollutant emissions control, and practical operational problems.

INTRODUCTION

Throughout the history of the development and use of jet aircraft engines, there has been, with a brief exception, an abundant supply of high-quality petroleum middle-distillates to fuel these engines. The availability of these high-quality middle-distillates is expected to diminish toward the end of this century because of diminishing overall supplies of crude oil and the resulting competition for minimally - refined portions of the petroleum barrel. In fact, because of changing sources of crude oil supply, there has been a trend over several years toward higher aromatics content in Jet A fuel delivered to airports to the extent that waivers of ASTM standards have had to be issued.

To offset a shortage of fuels obtained through straight distillation, higher-boiling-point fractions could be cracked and hydrogenated to force them to meet present specifications; however, these would be expensive and high-energy-consuming processes. An alternative is to modify the jet engine, in particular the combustion system, to accept fuels with less stringent specifications. This course would involve large initial expenditures for combustion system development and modification of in-use engines designed for the use of higher-quality fuels, but would have the benefit of reduced fuel-processing costs over the lifetime of the engine. It is entirely possible that the optimum choice will be a compromise, with some fuel treatment and some combustion system modifications. The Broad-Specification Fuels Combustion Technology Program was initiated by NASA to define the combustion system technology required to accommodate broadened-properties fuels with minimal processing, so that the trade-offs between extensive fuel processing to present specifications and combustion system modification with relaxation of fuel specifications can be evaluated.

The Broad-Specification Fuels Combustion Technology Program is a two-phase program involving parallel contracted efforts by the Pratt & Whitney Aircraft Group of the United Technologies Corporation and the Aircraft Engine Business Group of the General Electric Company. This paper is an assessment of the Phase I test results obtained by both contractors, in terms of severity of several fuels-properties effects on combustor performance or liner life. Design techniques with the potential to offset adverse fuels effects are described. The rationale for selection of combustion system concepts to be pursued in Phase II refinement testing is presented, taking into account the relative costs and complexities of the concepts, the current outlook on pollutant emissions control, and practical operational problems.

Because of the extent of the testing accomplished in the Phase I program with the two contractors, and the limitations on the length of a paper of this type, it is not possible to describe in detail all of the numerous combustor modifications and their effects on the ability of the several combustor concepts to use broadened-properties fuels. Neither is it possible to review the test results for every one of the many parameters of interest in the program. Accordingly, although a large part of the Phase I Program effort was devoted to reduction of emissions, a discussion of emissions results will be omitted from this paper, except for a few brief remarks in the concluding sections. Instead, the purposes of this paper are to:

(1). Present some of the more significant results showing the effects of the use of broadened-properties fuels on combustor performance and durability characteristics.

(2). Make some general statements concerning combustor design modifications effective in reducing the sensitivities of these characteristics to fuels properties changes.

(3). Discuss what the results of Phase I, considered along with changes in emissions regulations, mean to future combustor design philosophy and, therefore, what will be the direction of the Phase II effort.

(4). Call attention to the availability of the Phase I program final reports (references 1 and 2), for more detailed information.

PROGRAM DESCRIPTION

Program Objective

The objective of the program is to evolve the combustion system technology required to use fuels with moderate ranges of broadened properties in the engines used on current and future large commercial aircraft.

Program Plan

The program is being conducted in two phases. Two contractors are involved in both phases of the program, the General Electric Company, using their CF6-80 engine combustion system as a baseline design, and Pratt & Whitney Aircraft, using their JT9D engine combustion system as a baseline design for Phase I (changed to PW2037 engine combustion system for Phase II baseline).

Phase I: Combustor Concept Screening Testing. This phase consisted of a series of designs, tests, design modifications and retests to determine the best configurations for further evaluation, based on ability to use broadened-properties fuels while meeting program performance and emissions goals, and having suitable durability characteristics. Phase I has been completed, and an assessment of its test results is the purpose of this paper.

Phase II: Combustor Optimization Testing. Phase II was originally intended to be used for optimization of the best designs of Phase I in preparation for engine testing in a planned third phase of the program. Because of budgetary and other considerations, Phase III engine testing has been deleted from the program. This has caused Phase II to be redirected, with refinement of the better Phase I designs still a part of the program, but with an eye toward even more advanced technology. For example, the baseline combustor design for the P & WA effort has been changed from the JT9D combustor to the latest-technology PW 2037 combustor. Also, an advanced P & WA combustor concept (reference 3), which is essentially an aerodynamically-staged, rather than mechanically-staged, combustor has been incorporated into Phase II testing. Phase II testing is now in progress, and is scheduled to be completed by the end of 1983.

Program Goals

The program performance goals are listed in Table I, and the program emissions goals for the CF6-80 and JT9D combustion systems are given in Table II. The emissions goals reflect the Environmental Protection Agency (EPA) emissions standards proposed at the time of the initiation of this program (reference 4).

Combustion System Configurations

Each contractor was asked in Phase I to propose three combustion system concepts for screening testing, along with several modifications of each concept. The concepts were to have varying degrees of potential for accomplishing the program goals, and were expected to involve varying degrees of developmental difficulty and risk. One concept was to involve relatively minor modifications to the baseline combustion system, the intent being to determine what could be done in the event that current in-service engines were to find it necessary to use broadened-properties fuels. The other test concepts were to be "more advanced" and "highly advanced" designs, which would presumably be used only in entirely new engine designs.

The combustion system concepts selected are decribed in some detail in reference 5, and in greater in references 1 and 2. Table III summarizes the selections. Under Concept I, there were actually two JT9D engine combustors tested. The first, referred to in this paper as the "production" combustor, is a design used in most of the JT9D engines in use today. Only one test was conducted with this combustor, the purpose of which was to establish baseline data for the program that could be compared with in-service experience. The remainder of the Concept I tests were conducted with a second single-stage combustor, referred to as the "advanced bulkhead" combustor, used in recent versions of the JT9D engine. Under Concept II, the "staged Vorbix for E^3" refers to the series-staged combustor used in the NASA - P & WA Energy Efficient Engine (E^3) program (reference 6). This combustor was borrowed intact from that program to be tested with broadened-properties fuels. The "Double-Annular Staged" refers to a parallel-staged combustor of a type developed in the NASA -GE Experimental Clean Combustor Program (reference 7). Under Concept III, the CF6-80 Variable-Geometry Combustor featured a remotely-operated variable-area swirler to provide a range of primary-zone equivalence ratios. In the JT9D concept, changes were made manually to simulate the limits of variability, and a variable-airflow aerating fuel injector was evaluated.

Program Fuels

Table IV gives a partial list of typical properties values for the program fuels. These fuels cover a rather significant two percent range of hydrogen content, but are moderate in the sense that they do not extend into the area of coal-derived or other so-called synthetic fuels. Jet-A fuel was used for comparison with known baseline engine combustion system data and to establish baseline program data. The 12.8 percent hydrogen content fuel is the Experimental Referee Broad Specification (ERBS) fuel established by the Jet Aircraft Hydrocarbon Fuels Technology Workshop (reference 8), convened at the NASA Lewis Research Center in June 1977. The purpose of this workshop was to establish a reference broadened-properties fuel which would permit comparison of test results from numerous experimenters. The other two test fuels, referred to in this paper as ERBS 12.3 and ERBS 11.8, are blends of ERBS fuel and a high-aromatics blending stock. Detailed measured fuels properties can be found in references 1 and 2.

Radiant Heat Flux, Liner Temperature, and Effect on Liner Life

The effect of fuels properties variations on radiant heat flux and, consequently, combustor liner temperatures, was the most important effect documented in Phase I testing. This importance stems from the very large impact on estimated combustor liner life that may be caused by what might seem to be modest increases in liner temperatures. Estimating liner life is a very difficult undertaking if done without prior knowledge of the characteristics of the combustor in question. Much depends on whether maximum temperatures occur at locations where stress concentrations are also high, on how close the liner is to its maximum allowable temperature, and whether the maximum temperature is very localized or if that level of temperature is widespread. Also to be considered is the definition of exactly what constitutes failure in a given combustor. On the other hand, if one starts with knowledge of liner life under a given set of conditions, with a known temperature pattern, estimating liner life under operation at another temperature level is considerably more dependable. In this program, the contractors were dealing, in the case of the single-stage combustors, with well-known combustor characteristics, and with methods of calculation with which they have had experience (reference 9 describes a method used by the General Electric Company). Because of this, the liner life estimates presented in this section, while sometimes startling considering the modest liner temperature increases, are considered to be realistic estimates. References 1 and 2 discuss radiant heat flux and liner temperature data in great detail. In this section, only enough examples will be presented to indicate the magnitude of the problem.

Radiant heat flux values are plotted as a function of fuel hydrogen content in Figure 1 for the JT9D baseline single-stage combustors (combustor configuration designations used in this paper are those use by the respective contractors in reference 1 and 2). These include the JT9D "production" combustor (configuration SS-1), used in most of the JT9D engines currently in use, the JT9D "bulkhead" combustor (configuration SS-2), used in recent versions of that engine, and the initial simulated variable-geometry build (configuration VG-1), which is identical with configuration SS-2, except that all the fuel was injected through the secondary passage of the duplex fuel nozzle, hence the "single pipe" designation. It can be seen that radiant heat flux increases with decreasing fuel hydrogen content in all cases, but that the increment between Jet-A and ERBS fuels is large compared with the increment between ERBS and ERBS 11.8, even though the change in hydrogen content is similar. Several possible explanations for this situation have been considered:

(1) **Delayed Heat Release** - Slower rates of burning in the lower hydrogen content fuels might cause the point of highest heat release to move downstream, and thus not be "seen" as well by the radiometer. This does not seem likely, as thermocouple readings gave no evidence of temperature shifting.

(2) **Saturated Particulate Concentrations** - As production of particulates increases with lower hydrogen content fuels, a saturation point is reached at which emissivity of the combustion products approaches that of a blackbody, limiting additional heat transfer.

(3) **Fuel Composition Effects** - The decrease in hydrogen content between Jet A and ERBS reflects primarily a difference in multi-ring aromatics, with a large increase in naphthalenes. For the ERBS 12.3 and ERBS 11.8 fuels, total aromatics increase substantially, but naphthalenes increase only slightly, implying that the total aromatics increase is caused by changes in single-ring aromatics. Since multi-ring aromatics have a greater propensity for particulate formation than single-ring components, there might be a larger increase in radiant heat flux in going from Jet-A to ERBS than in going from ERBS to ERBS 11.8.

The first explanation is not considered likely. It is not known whether either or both of the other two possibilities apply in the present case.

An example of how the radiant heat flux data of figure 1 translate into liner temperature differentials is shown in figure 2, in which average liner temperatures for the same combustors are given. As would be expected, the dilution-zone liner temperatures are not affected to much of an extent, since the downstream panels do not "view" the reaction zone directly. One anomaly in this figure is the flat primary-zone temperature curve at take-off for the production combustor (configuration SS-1), even though figure 1 shows it to have a continuously-increasing radiant heat flux with decreasing fuel hydrogen content.

A clearer picture of actual values of the temperature increases relative to Jet-A temperatures is given in figure 3 for the JT9D bulkhead combustor at takeoff. Liner life reduction estimates are given in Table V for this combustor in the SS-2 and VG-1 configurations. The much higher estimates for life reduction based on maximum temperatures as compared with those based on average temperatures indicates the benefits of reducing local high temperatures even if average temperature levels are not significantly reduced.

Radiant heat flux data for the final configuration of the CF6-80 single-stage combustor are shown in figure 4. Data for all fuels were not obtained at all conditions because of failure of the radiometer during testing of this configuration. Note that available data are well-ordered with respect to hydrogen content. Figures 5 and 6 present data for average and maximum liner temperatures for the baseline CF6-80 single-annular combustor configuration (S-1) and the final configuration of the combustor (S-10), respectively. Two points are significant here: (1) the data in all cases are well-ordered with respect fo hydrogen content, and (2) the sensitivity of both average and maximum temperatures has been greatly reduced during Phase I development.

The huge significance of this reduction in sensitivity is made clear in figure 7, in which liner life reduction estimates are shown for the two configurations when changing from Jet-A to ERBS fuel. Whereas the temperature increase shown in figure 5 for configuration S-1 would be expected to lead to a liner life reduction in excess of 30 percent, the much lower temperature increase shown in figure 6 for configuration S-10 would be expected to cause only about a three percent loss.

A comparison of sensitivities of the three CF6-80 combustor concepts to fuel hydrogen content is illustrated in figure 8. In this figure, the differential between maximum liner temperature and combustor inlet temperature when using a particular test fuel is rationalized by the differential obtained when using Jet-A fuel, and then plotted as a function of fuel hydrogen content. Also shown for each configuration is the value of the differential with Jet-A to indicate the liner temperature level. For each combustor concept, data are shown for both baseline or other early configuration and for the final configuration. For the double-annular concept, liner temperature sensitivity to fuel hydrogen content essentially was not present even in the initial configuration. This was an anticipated result because of the basic design feature, a lean-burning main combustion zone in which most of the fuel is burned at high-power conditions. This feature, which was originally intended for NO_x reduction, also tends to minimize carbon particle formation and resulting radiant heat flux ordinarily produced in high-equivalence-ratio designs. In this particular combustor, the liner temperature level is higher than desired, negating the benefits of low sensitivity to fuels properties; however, the high level can be reduced through developmental changes without compromising the excellent lack of fuels properties sensitivity, and in fact was lowered significantly from configuration D-2 to configuration D-5 without detriment to sensitivity.

The single-annular and variable-geometry combustor concepts had a large sensitivity to fuel hydrogen content in their initial configurations. In each case, subsequent development caused this sensitivity to disappear. Some part of the improvement in these concepts (as well as in the JT9D concepts) appears to have been accomplished through atomization, mixing, and liner convective heat transfer improvements; however, by far the largest effect was obtained through the use of a ceramic thermal barrier coating on the liners. This coating, in addition to lowering the level of liner temperatures significantly, also had the effect of essentially eliminating sensitivity of peak liner temperatures to fuels properties. For single stage configuration S-10, there was a spread in maximum liner-to-inlet differential of only 6 K for the four test fuels, whereas this spread had been 64 K for configuration S-1. As with the double-annular concept, the level of peak liner temperatures was decreased.

It should be noted that, while the thermal barrier coating eliminated sensitivity of maximum liner temperatures to fuels properties in all cases, this was not true of average liner temperatures. In addition, there was some movement of peak liner temperature location after application of the coating. Consequently, the exact effect of its use on liner life is difficult to estimate. Also to be considered are possible changes in the reflectivity of such coatings during long-term use, which would tend to diminish the effectiveness of the coating.

The variable-geometry combustor initial configuration (V-1) showed a fuels properties sensitivity very like that of the single-stage combustor. In theory, the sensitivity characteristics of the variable-geometry combustor should be more like those of the double-annular combustor, inasmuch as the objective of a variable-geometry design is to obtain the advantages of the staged-type combustors (optimization of reaction-zone equivalence ratio at both low- and high-power operation) without the attendant complexity, multiple fuel zones, and intermediate - power problems. This combustor acted more like a fixed-geometry single-stage design, probably because the primary-zone equivalence ratio was somewhat higher at take-off conditions than the design value, thus losing some of the expected lean-burning-zone characteristics enjoyed by the staged combustor. For configuration V-8, the high-power equivalence ratio was even higher, because of attempts to improve idle emissions; however, although the liner temperature level was much higher than with configuration V-1, sensitivity of peak liner temperature to fuels properties was again eliminated, principally through the use of a thermal barrier coating. The final liner temperature levels of the single-stage and variable-geometry combustors was essentially the same. It would be expected that further development of the variable-geometry combustor concept would produce a leaner burning at high-power conditions, beneficial to both reduction of the high smoke levels obtained in configuration V-8 with ERBS fuels, and reduction of liner temperature level.

Smoke Emissions

With the exception of the CF6-80 Variable-Geometry combustor, which was in a very early stage of development, all of the combustor concepts final Phase I configurations were well within their program smoke goals. Fuels properties effects were less clear in the case of smoke emissions than with other emissions. While smoke numbers with ERBS fuel were generally slightly higher than those with Jet-A, the values obtained with ERBS 12.3 and ERBS 11.8 did not follow a consistent pattern. In some cases, particularly in configurations with higher levels of smoke, there appears to be a consistent increase in smoke number with decreasing hydrogen content. In other cases, the smoke number obtained with ERBS 12.3 and ERBS 11.8 was lower than that of ERBS, and even lower than that of Jet-A. While the smoke points of the ERBS fuels are not widely separated from each other, that of Jet-A is much higher; therefore, experimental error might account for ERBS 12.3 and ERBS 11.8 being somewhat lower in smoke number than ERBS, but in no way for their being lower than Jet-A. Also, although it would not completely explain the above anomalies, a better understanding is required concerning the effect on smoke of type of aromatics present, rather than quantity of aromatics alone. As mentioned in the discussion of radiant heat flux data, the decrease in hydrogen content between Jet-A and ERBS reflects primarily a difference in multi-ring aromatics, with a large increase in naphthalenes. For the ERBS 12.3 and ERBS 11.8, total aromatics increase substantially, but naphthalenes increase only slightly, implying that the total aromatics increase is caused by changes in single-ring aromatics.

Exit Temperature Pattern Factors and Radial Profiles

Combustor exit temperature pattern factors were affected only slightly in the single-stage combustors (maximum increase of 0.05 in going from Jet-A to ERBS 11.8), and were essentially not affected in the CF6-80 Double-Annular and Variable-Geometry combustors. The P & WA Staged Vorbix combustor exhibited erratic temperature pattern-profile data, possibly because of fuels-properties sensitivity of fuel dispersion and atomization processes which occur in the main-stage fuel-injection carburetor tubes.

Effects of fuels properties on exit temperature radial profiles were negligible.

Combustion Stability

Idle Blowout. For all configurations, blowout fuel-air ratio was recorded at idle conditions as a measure of relative primary- or pilot-zone stability. The effect of variation in fuels properties was not significant, with a maximum increase in blowout fuel-air ratio of 0.0008 in going from Jet-A to ERBS 11.8. In cases in which differences did occur, the fuel-air ratio did not increase consistently with decreasing hydrogen content. Instead, there generally would be a noticeable increase between Jet-A and ERBS, with much less increase (or even a drop-off) between ERBS and the two ERBS blends. While the viscosity of the ERBS fuel is higher than that of Jet-A, viscosity actually decreases in going from ERBS to the ERBS blends, even though their hydrogen contents are lower than that of ERBS. Also, the initial boiling point of the ERBS 12.3 and ERBS 11.8 fuels is lower than that of the ERBS fuel. Both of these circumstances tend to explain the blowout results described above, as well as other anomalies mentioned in subsequent paragraphs.

Altitude Blowout. Blowout tests were conducted on one of the later configurations of the CF6-80 single-annular combustor at altitude conditions. Figure 9 shows that the effect of fuels properties in going from Jet-A to ERBS fuel is enough to increase blowout pressure to above the goal for engine performance. The small differences in results with ERBS 11.8 and ERBS fuels compared with the difference between ERBS and Jet-A, the increment in hydrogen content being the same in both cases, may be caused by the viscosity and volatility trends mentioned above. The difference in blowout pressure between the ERBS fuels and Jet-A in figure 9 corresponds to roughly 1000 meters altitude change. Similar results were obtained in testing of the JT9D configurations. Again, anomalies occured with the ERBS 11.8 fuel.

Sea-Level Cold Start. A test at sea-level cold-start conditions was conducted on one of the later configurations of the JT9D bulkhead single-stage combustor. Air and fuel temperatures were held at 250 K. Figure 12 shows data for "time to ignition" as a function of fuel flow. Although there were clear differences in the amounts of fuel required, ignition in reasonably short time was accomplished with all fuels at fuel flows below the nominal start values for the JT9D engine.

IMPACT OF PHASE I TESTS RESULTS ON FUTURE COMBUSTION SYSTEM DESIGN

The selection of combustion system concepts and emissions goals made at the beginning of the program was greatly influenced by the EPA proposed emissions regulations in existence at that time. Certainly the main impetus for considering the use of a staged or variable-geometry combustor is the ability to burn lean enough at high-power conditions to meet NO_x regulations, because it is unlikely that the formerly-proposed limits for both idle CO and HC and high-power NO_x can be met in a single-stage fixed-geometry combustor. Recently, the EPA has issued "final" emissions regulations (reference 10) which are concerned only with HC and smoke emissions. Without the encumbrance of NO_x limitations, the use of staged or variable-geometry combustors is not attractive from an emissions standpoint alone. From the standpoint of the ability to accommodate the use of broadened-properties fuels, the staged and variable-geometry combustors have merit, since the lean burning capability, in addition to reducing NO_x emissions, also reduces radiant heat flux and liner temperature levels as well as their sensitivity to fuels properties. This, however, would not justify their use if modification of the current production-type single-stage combustion systems to accomplish the same results (except for NO_x reduction) is feasible.

Phase I testing demonstrated that relatively minor modifications to production-type combustors can offset the effects of broadened-properties fuels with the ranges of properties encompassed by the ERBS and ERBS-blends fuels. As always, primary-zone equivalence ratio increases (up to a value of 1.0) can be used to reduce idle emissions and enhance combustion stability. Of course, this tends to increase smoke and liner temperatures; however, judicious primary-zone dilution pattern selection, better mixing, and improved atomization have been effective in reducing smoke and liner hotspots, even in cases in which average liner temperature was not reduced. The use of ceramic thermal barrier coatings was very effective in both lowering liner temperature levels and reducing sensitivity of liner temperatures to fuels properties. The combustion system designer would no doubt prefer to design without liner coatings, keeping them as an "ace in the hole", to be used if liner durability problems crop up after the design has been fixed and is in production; however, liner coatings are now used as a matter of course in some production combustors, and in a choice between coating current production liners and initiating complex advanced designs, the coatings would win rather easily. Nonetheless, the limitations of such coatings must be recognized. More effective liner-cooling techniques would certainly be welcome, particularly since future combustion systems are expected to be required to have higher cycle pressures and temperatures. This will not only place a heavier burden on engine hot parts, including combustor liners, but will also cause less air to be available for liner cooling and downstream dilution for exit temperature profile tailoring.

For such future combustion systems, the staged and variable-geometry combustors may be required. At one time, designers were reluctant to discuss the use of variable geometry in combustion systems because of the high-temperature environment and consequent difficulty of maintaining reliability of operation. In recent years, however, many research programs have been conducted using variable geometry, and confidence in its eventual practicality has grown. Certainly, from the standpoint of the combustion engineer, its use must be considered when the alternative choice is a typical staged combustor, with multiple fuel zones, potential thermal stability problems, and intermediate-power performance shortcomings.

Because of these considerations, it is likely that, for current engine operating conditions, single-stage fixed-geometry combustion systems will continue to be used even if fuel quality declines considerably. For future higher-temperature and -pressure cycles, variable-geometry combustors or some other innovative type of combustor will probably be required. These considerations led to the choice of combustors to be tested in Phase II of the program. When it was decided that the originally-intended Phase III engine testing segment of the program would not be implemented, and therefore the need to choose Phase II designs that would safely operate in the baseline engines disappeared, the opportunity to pursue somewhat more innovative technology presented itself. Thus, the decision was made to drop the CF6-80 double-annular combustor, in spite of excellent ability to accommodate broadened-properties fuels, and to continue refinement of the single-stage production-type combustor and the variable-geometry combustor in the GE Phase II program. In the P & WA Phase II program, the baseline engine was changed from the JT9D to the latest-technology PW 2037, and the combustion systems to be tested are a single-stage variable-geometry combustor and a PW2037-sized version of an advanced combustor, which is a staged combustor, but is staged aerodynamically, rather than mechanically, and has a single fuel-supply system. It thus attempts to take advantage of both the lean-burning capabilities of the usual staged combustors and the relative simplicity of single-stage combustors.

CONCLUDING REMARKS

Some general statements can be made concerning Phase I test results:

1. Combustor liner temperatures and altitude blowout limits were significantly affected by fuels properties changes.

2. Idle CO and HC, and high-power NO_x and smoke were increased slightly (usually 10 to 30 percent) by fuels properties changes.

3. Idle blowout fuel-air ratio, and exit temperature pattern factors and radial profiles were essentially not affected by fuels properties changes.

4. Relatively minor design modifications to the single-stage production combustors were identified which significantly reduced sensitivity of the emissions and performance parameters listed above to fuels properties variations. Exceptions were high-power NO_x, and altitude blowout. The latter is expected to respond to further fuel atomization development.

5. The advanced staged and variable-geometry combustor concepts showed great potential for meeting all program performance, durability, and emissions goals with reasonable development.

6. Considering present EPA emissions regulations, single-stage fixed-geometry combustion systems are likely to remain in use for some time even in the event of fuels properties changes of the magnitude encompassed in this program.

7. Advanced combustion system concepts may be required for use in future higher-temperature and -pressure engine cycle applications, particularly with the use of broadened-properties fuels.

One very important potential problem not addressed in this program is the effect of fuels properties variation on fuel thermal stability. Broadened-properties fuels would be expected to have a greater tendency toward cracking, with resulting plugging of fuel system components. It was not feasible in this program to conduct the long-term tests required to establish whether a thermal stability problem exists.

Other factors which must be considered in interpreting the test data have been mentioned several times in this paper. These have to do with the difficulties encountered in acquiring fuels blends in which levels of all desired properties are obtained simultaneously. In the ERBS fuel itself, essentially all the desired properties levels have been reached. In the ERBS 12.3 and ERBS 11.8 blends, however, both viscosity and initial boiling point are somewhat lower than desired. Also, while the blends would appear to have the appropriate levels of aromatics, the required increases in aromatics for these two fuels were obtained with increased amounts of single-ring aromatics, whereas the increase between Jet-A and ERBS fuel was obtained basically with multi-ring aromatics. More information is required on the possibly different fuels properties effects caused by single- and multi-ring aromatics. In Phase II of this program, fuels with significantly higher viscosity levels, but with similar hydrogen content, to the ERBS fuels, will be used in some tests to attempt to isolate the effect of viscosity on various parameters. The other questions mentioned above are being addressed in other NASA programs.

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TABLE I. - DESIGN PERFORMANCE GOALS

- Combustion efficiency, as computed from emissions measurements, greater than 99 percent at all operating conditions.
- Total pressure loss no more than 6 percent at sea-level take-off conditions.
- Combustor-exit-temperature pattern factor, (T_{T4} max - T_{T4} av.)/(T_{T4} avg. - T_{T3} avg.), no more than 0.25 at sea-level take-off conditions.

T_{T3} avg.	Average measured total temperature at combustor inlet
T_{T4} avg.	Average measured total temperature at combustor exit
T_{T4} max.	Maximum individual measured total temperature at combustor exit

- Combustor-exit average radial temperature profile consistent with that required of the production combustor of the selected engine (to be specified by the Contractor)

TABLE II. - DESIGN EMISSIONS GOALS

	CF6-80 PRODUCTION COMBUSTOR JT9D "BULKHEAD" COMBUSTOR	CF6-80 DOUBLE-ANNULAR AND VARIABLE-GEOMETRY COMBUSTORS ENERGY EFFICIENT ENGINE STAGED "VORBIX" AND JT9D VARIABLE-GEOMETRY COMBUSTORS
HC	6.7	3.3
CO	36.1	25.0
NO_x	35.3 (CF6-80) 33.0 (JT9D)	33.0
SN	19.2	19.2

HC	Total unburned hydrocarbons (g/KN)	EPA Parameter
CO	Carbon monoxide (g/KN)	
NO_x	Total oxides of nitrogen (g/KN)	
SN	SAE smoke number	

TABLE III. - COMBUSTION SYSTEM CONCEPTS

	TYPE OF DESIGN	APPLICATION
Concept I	Minor modifications to production combustor (JT9D and CF6-80 engine combustors)	In-service engine
Concept II	More advanced (JT9D: Staged Vorbix from E^3 CF6-80: double-annular staged)	Future engines
Concept III	Highly advanced (JT9D and CF6-80 variable-geometry single-stage)	Future engines

TABLE IV. - COMPARISON OF JET A AND BROADENED-PROPERTIES TEST FUELS

FUEL PROPERTY	JET A	BROADENED-PROPERTIES TEST FUELS		
		ERBS	ERBS	BLENDS
Hydrogen content, wt%	13.5-14	12.8	12.3	11.8
Aromatics content, vol%	19	31	41	51
Naphthalene content, vol%	1	11	14	16
Initial boiling point, K	446	435	436	430
Final boiling point, K	540	601	606	609
Viscosity, cS, 250 K	5-7	8.8	7.9	7.0

TABLE V. - PROJECTED EFFECT OF USE OF ERBS FUEL VS JET A ON LIFE OF JT9D ADVANCED BULKHEAD COMBUSTOR LINER

Configuration	SS-2	VG-1
Fuel injection mode	Duplex	Single Pipe
Based on average liner temperature increase		
temperature increase K (°F)	7 (12)	12.3 (22)
reduction in life - %	6	11
Based on maximum liner temperature increase		
temperature increase K (°F)	15 (27)	40 (72)
reduction in life - %	13.5	36

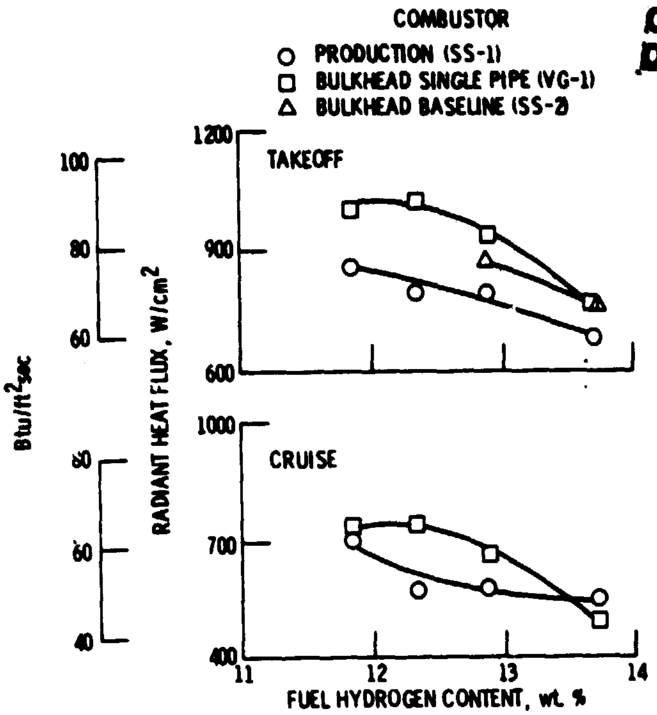


Figure 1. - Radiant heat flux to liner in primary zone of the three JT9D baseline single stage combustors.

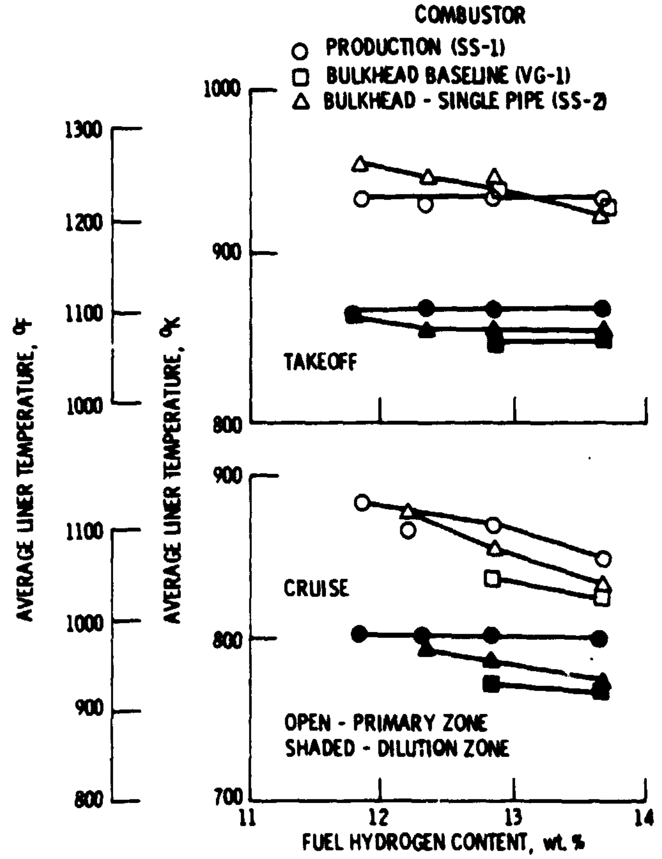
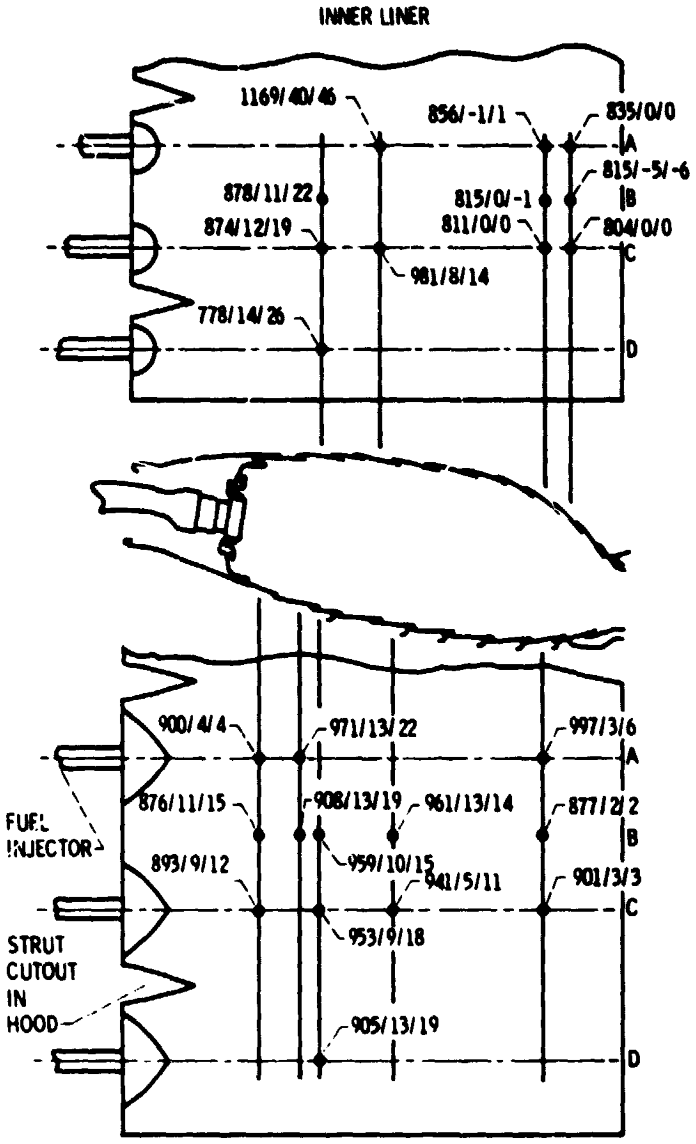


Figure 2. - Effects of fuel composition on average liner temperatures in the three JT9D reference combustors.



TEMPERATURES XXX/YY/ZZ IN °K
XXX = TEMPERATURE WITH JET A FUEL, YY = INCREMENTAL INCREASE JET A TO ERBS, ZZ = INCREMENTAL INCREASE JET A TO ERBS 11.8

Figure 3. - Liner temperature distribution in advanced JT9D bulkhead combustor at takeoff.

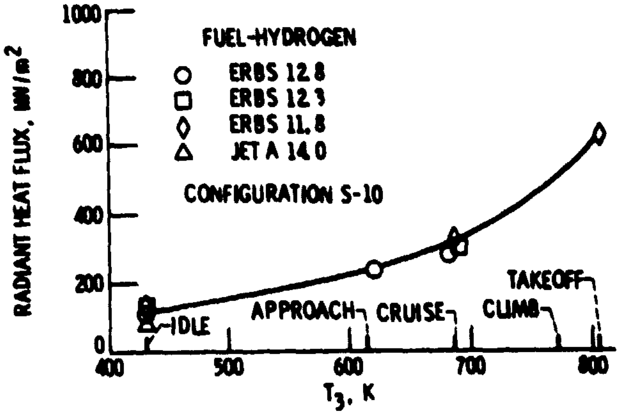


Figure 4. - CF6-80 single annular combustor primary zone radiant heat flux.

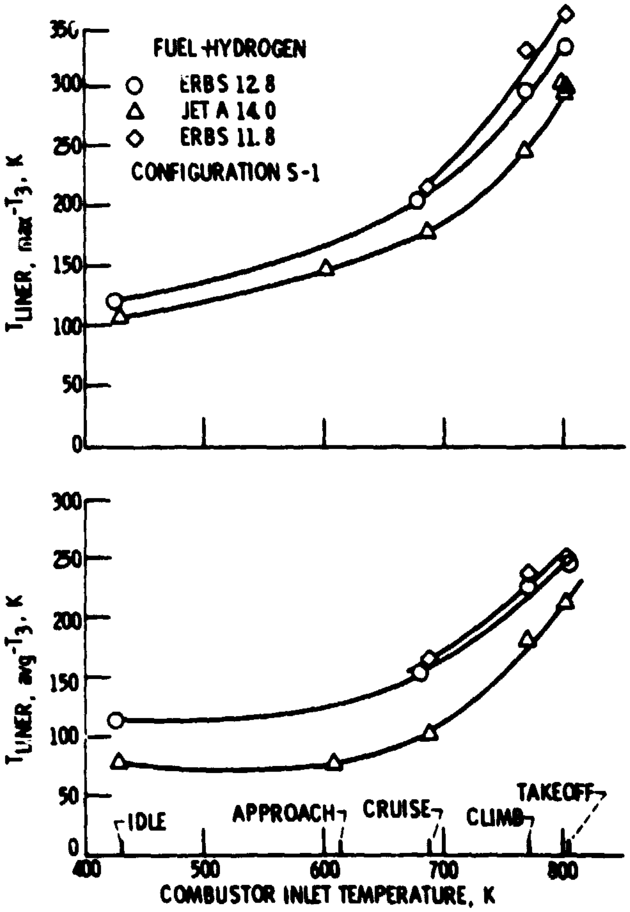


Figure 5. - CF6-80 configuration S-1 liner temperatures.

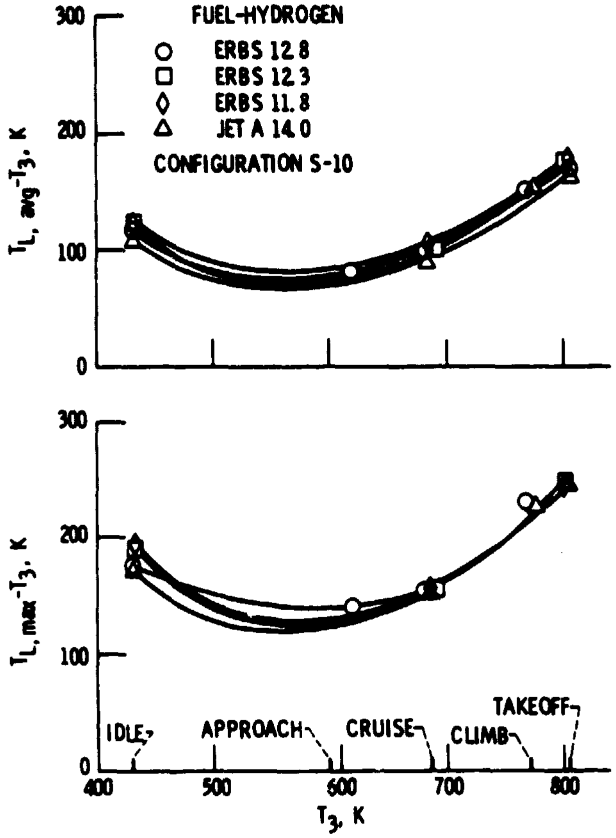


Figure 6. - CF6-80 single annular combustor average and maximum liner temperatures.

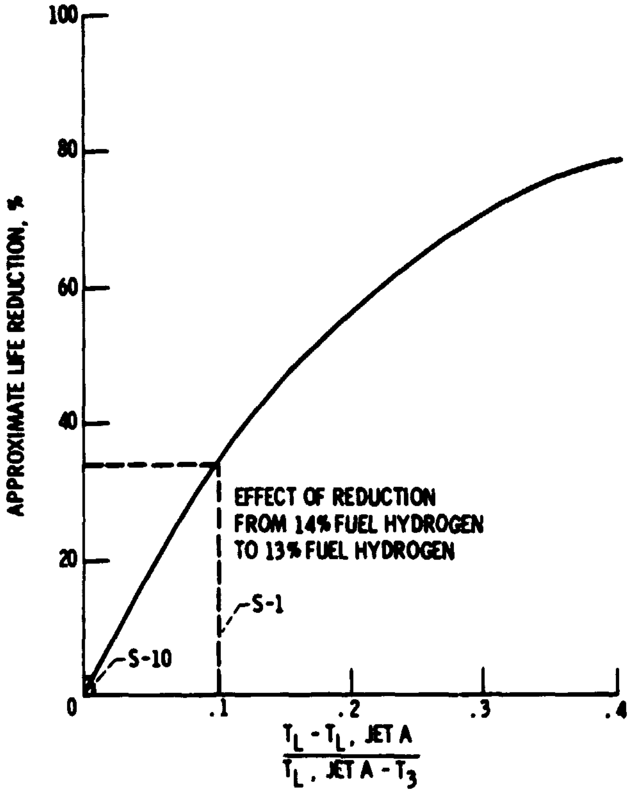


Figure 7. - Effect of liner temperature parameter on CF6-80 single annular combustor life.

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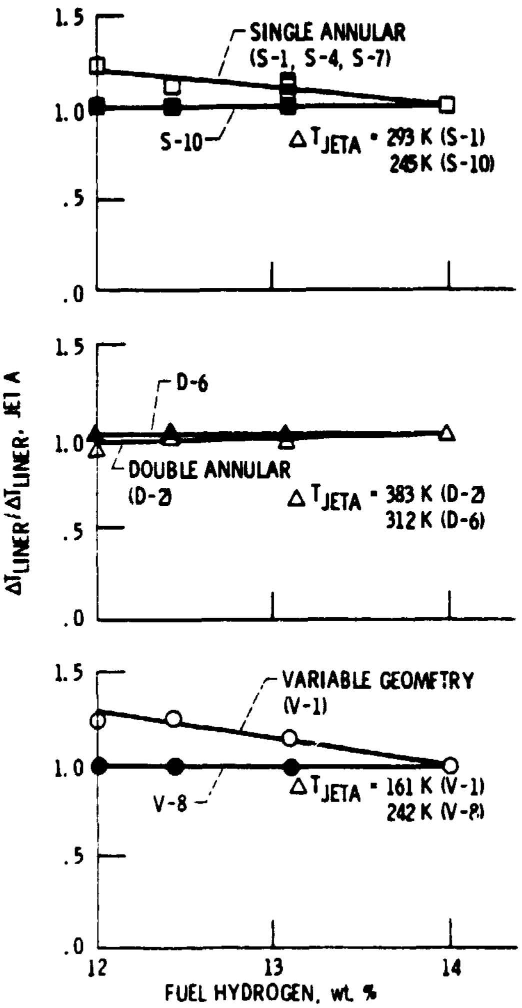

Figure 8. - Sensitivity of peak liner temperature rise to fuel hydrogen content, CF6-80 combustor concepts.

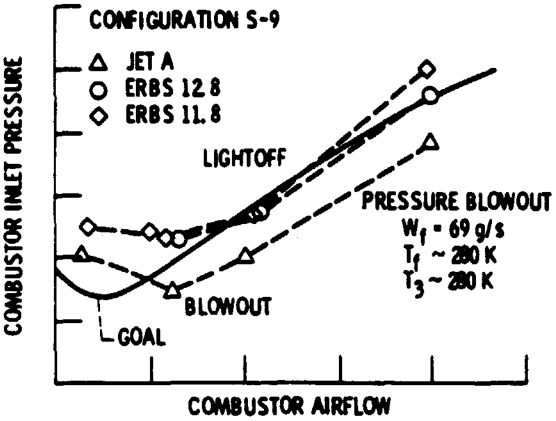

Figure 9. - Effect of fuel hydrogen content on CF6-80 single annular combustor altitude relight/blowout.

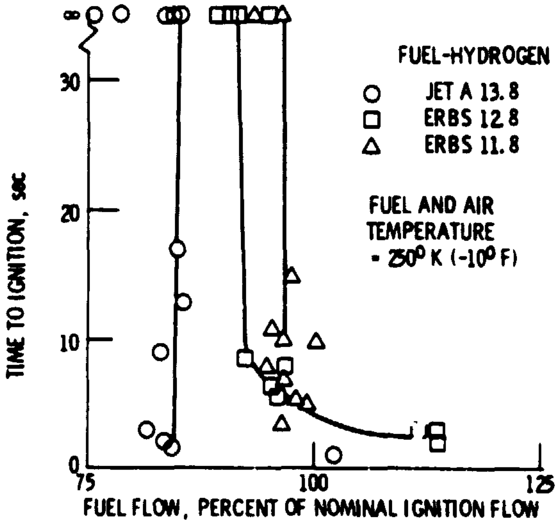

Figure 10. - Sea level ignition characteristics of JT9D single stage combustor configuration SS-7.