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ANALYTICAL AND EXPERIMENTAL EVALUATIONS OF THE EFFECT OF BROAD PROPERTY FUELS ON COMBUSTORS FOR COMMERCIAL AIRCRAFT GAS TURBINE ENGINES

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ANALYTICAL AND EXPERIMENTAL EVALUATIONS OF THE EFFECT OF BROAD PROPERTY FUELS ON COMBUSTORS FOR COMMERCIAL AIRCRAFT GAS TURBINE ENGINES

by

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Abstract

Analytical and experimental studies were conducted in three contract activities funded by the National Aeronautics and Space Administration, Lewis Research Center, to assess the impacts of broad property fuels on the design, performance, durability, emissions and operational characteristics of current and advanced combustors for commercial aircraft gas turbine engines. The effect of fuel thermal stability on engine and airframe fuel system was evaluated. Trade-offs between fuel properties, exhaust emissions and combustor life were also investigated. Results indicate major impacts of broad property fuels on allowable metal temperatures in fuel manifolds and injector support, combustor cyclic durability and somewhat lesser impacts on starting characteristics, lightoff, emissions and smoke.

Summary

Analytical and experimental studies were undertaken to evaluate the impact of broad property fuels on the design and performance of current and advanced technology combustors operating in widebody-jet aircraft engines. As a result of the studies, several combustors were designed and subsequently evaluated with conventional and broad property fuels at widebody-jet engine operating conditions. Results obtained indicated that lean burning, low emission double annular or dual stage combustion systems can accommodate a rather wide variety of broad property fuels without a serious deterioration of performance or a serious increase in exhaust emissions. Rich burning single annular design concepts appeared to be somewhat less tolerant to the use of broad property fuels, because increased radiant heat load on the liners produced by these fuels requires an increase in liner cooling air to control liner temperatures. As a result, emissions levels increase and the ability to control exit temperature pattern factor is impaired. Based on test results of pollutant emissions and combustor durability, the premix combustor design concept is judged to be the most tolerant when used with broad property fuels. However, this concept would require additional development efforts to meet the reliability and durability objectives of the widebody-jet-engines.

Finally, the reduced thermal stability of broad property fuel, relative to Jet A, is predicted to require a reduction in the allowable metal temperatures in fuel manifolds and injector support by as much as 30°K. Approaches involving rejection of the engine lubricating system heat to the airframe fuel tanks and the use of non-recirculating fuel pumps were suggested for minimizing this problem.

Introduction

This report summarizes the results of two sequential research studies conducted under contract by the National Aeronautic and Space Administration Lewis Research Center aimed at assessing the impacts of broad property fuels on gas turbine combustion systems. The first study consisted of in-depth analytical evaluation of in-service and advanced combustors for wide body jet aircraft engines. The second study was an experimental effort in which advanced combustor concepts were evaluated with broad property fuels.

The supply, quality and cost of aviation turbine fuels through the turn of the century and beyond will be influenced by many factors. Some of these are diminishing petroleum supplies, increasing demands on mid distillate products, changing characteristics of available crudes, limited refinery capabilities and properties of fuels derived from nonpetroleum sources. Thus in the future, in order to insure a more reliable and flexible fuel supply it may be necessary to use jet fuels with a broader range of properties. The use of these fuels could also minimize refinery energy consumption and processing costs.

Broadening fuel properties could however, result in degradation of propulsion system performance, durability and reliability. Thus it appears necessary to define the penalties associated with broad property fuels usage and to evolve the required technology for their usage.

The studies summarized herein assessed the impact of broad property fuels on the design, durability, emissions, and operational characteristics of combustors designed for wide body jet aircraft engines. These studies were conducted in two separate efforts. In the first effort, the General Electric Company (ref. 1) and the Pratt and Whitney Aircraft Group (ref. 2) conducted analytical studies designed to estimate the performance of combustor design concepts operating with broad property fuels. The reference engine cycles selected by General Electric (GE) for the analytical study were those of the General Electric CF6-50 and the NASA/GE Energy Efficient Engine (E^3). The Pratt and Whitney Aircraft (P&WA) Group selected the JT9D-7F and the NASA/P&WA Energy Efficient Engine (E^3). Combustor performance in terms of combustion efficiency, pollutant emission and smoke, and liner durability in terms of combustor liner temperatures were estimated.

The second effort was an experimental study (ref. 3) conducted by the General Electric Company to evaluate the effects of combustion zone design modifications on combustor performance, pollutant emission, and combustor durability while operating with broad property fuels. This study was conducted using General Electric's CF6-50C engine as the reference engine, a 36° sector of the double annular combustor developed under the NASA/G.E. Experimental Clean Combustor Program (ref. 4) as a test combustor, and two combustor modifications. Three test fuels with nominal hydrogen weight percentages of 12, 13 and 14 were used in the experimental study. Combustor performance with the various fuels was judged primarily on the basis of combustion efficiency, pollutant emissions (including smoke), and flame radiation as evidenced by changes in combustor liner temperature.

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

Analytical Study

Contractors and Engine Selection

Two contractors were chosen for the analytical phase of this study through competitive procurement procedures. They were the Aircraft Engine Group of the General Electric Company and the Pratt and Whitney Aircraft Group Commercial Products Division of United Technologies Corporation. The studies were conducted at GE's test facilities at Evendale, Ohio and at P&WA's test facilities at East Hartford, Connecticut. Each contract was nine months duration. Two high bypass axial-flow turbofan engines with high cycle pressure ratios were selected by each contractor. The first engine selected was a production engine that is currently in service with the commercial air carriers while the second engine represents an advanced engine designed to provide a reduction in specific fuel consumption and operating cost.

General Electric Aircraft Group

The General Electric Company selected the CF6-50C production engine and the NASA/GE Energy Efficient Engine (ref. 5). The CF6-50C engine has a 29.46:1 compression ratio, and is rated at 224kN thrust at standard sea level conditions.

The GE E^3 design is smaller in size than the CF6-50 and represents more advanced component design technology. The compression ratio for this engine is 29.80:1 and the rated thrust at standard sea level conditions is 152kN. Cycle operating conditions for the CF6-50C and the E^3 engine combustion systems are presented in Table 1.

Pratt and Whitney Aircraft

The Pratt & Whitney Aircraft Group selected the JT9D-7F engine which is described in reference 6, and an advanced Energy Efficient Engine which is described in reference 7. The JT9D-7F engine has a 22.3:1 compression ratio; and is rated at 197kN thrust at standard sea level conditions. The NASA/P&WA E^3 engine is smaller in size than the JT9D-7F, has a pressure ratio of 31.67:1 and contains advanced technology concepts in many of its components. Cycle operating conditions for the JT9-7F and the E^3 engine combustion systems are presented in Table II.

Study Fuels

Jet A and an aviation research fuel (broad property fuel) were selected to compare the results of the analytical studies. The research fuel was established at the Jet Aircraft Hydrocarbon Fuels Technology Workshop conducted at the NASA Lewis Research Center in June, 1977 (ref. 8). The use of this fuel permitted comparison of test results from several researchers. This research fuel allows for a decrease in the hydrogen content, 12.8%, an increase in the aromatic content of approximately 35% and an increase in the viscosity 12.0 mm^2/s at 250°K, relative to the current Jet A fuel properties, which are controlled by an average hydrogen content of 13.8 percent, an aromatic content of 25 percent maximum and a maximum fuel viscosity of 8 mm^2/s maximum at 253°K. The 10% boiling point of 477°K for the research fuel corresponds to a value of 277°K for Jet A. Fuel Specifications for reference fuels used in the analytical program are presented in the contractor's final reports (ref. 1 & 2).

Conceptual Combustor Designs

A total of twelve combustor configurations were analyzed by General Electric and a total of six combustor configurations were analyzed by Pratt & Whitney Aircraft. An abbreviated description of each configuration is given in Table III. Available combustion data in the literature on the use of fuels of various composition in combustion devices were used to establish and develop criteria for evaluations or revisions required in combustor designs to accomodate the broad property fuels. This information was used to establish the influence of fuel properties changes on combustor performance and operation to predict the revisions required in combustor designs to accomodate broad property fuels. For a complete discussion of the predictions, see the contractors' final reports of the study, GE reference 1 and P&WA reference 2.

General Electric Aircraft Group

The key combustion system design requirements selected for this study are generally representative of the design requirements of both the CF6-50C and the E^3 combustion systems, although in the case of the existing CF6-50C engines less stringent emissions requirements apply. In most cases, existing designs were available for these combustors but in some situations, particularly those involving the E^3 engine, these designs had to be scaled from other engine configurations.

The production combustor and five-conceptual combustor systems designed for the CF6-50C engine cycle were analyzed. In addition, six similar combustion systems for the E^3 cycle conditions were analyzed. The following combustor concepts were selected for these studies:

Concept 1. Baseline Single Annular Combustor
" 2. Short Length Single Annular Combustor
" 3. Annular slot Combustor with Premixing Fuel Injection
" 4. NASA/GE ECCP Double Annular Combustor
" 5. NASA/GE ECCP Radial/Axial Combustor
" 6. Premixing, Prevaporizing Variable Geometry Combustor

The design feature of each of these combustors are described in detail in reference 1.

Pratt & Whitney Aircraft Group

The JT9D-7F combustor concepts were designed to meet the requirements of the current production version of the JT9D-7F engine with no change in the compressor rear frame structure and no change in engine length. The E^3 combustor concepts were designed to meet the requirements of the NASA/P&WA E^3 engine design. The compressor exit dimensions and turbine inlet dimensions are typical for this series of advanced engine designs and the maximum combustion system length for the E^3 concepts was selected to preclude the necessity of making a drastic change in the engine frame structure.

The production combustor design and two-conceptual combustion systems designed for the JT9D-7F engine cycle were analytically evaluated. Three similar conceptual combustion systems designed for The NASA/P&WA E^3 Cycle conditions were also analytically evaluated. The following combustor concepts were selected by P&WA for this study:

Concept 1. Baseline Single Stage Combustor
Concept 2. Vorbix Combustor
Concept 3. Premixed Combustor

A complete discussion of the combustor design details, is presented in the final report of the P&WA analytical study (reference 2).

Analytically Predicted Impacts of the Broad Property Fuels

Thermal Stability of Broad Property Fuel

Based on data obtained from the literature (ref. 2) it is estimated that in order to minimize or avoid coke formation in fuel injectors, supports, and manifolds it is necessary to reduce the fuel passage temperatures to 345°K while using broad property fuel.

Experience with Jet A indicates to achieve the same condition the fuel passage temperature can be maintained at 375°K.

In active fuel systems, the coking rate has a strong temperature dependence. The reduced thermal stability of broad property fuels will require a reduction in surface temperature in the fuel systems components of about 30°K to achieve the level of coking protection currently obtained with Jet A.

Rejection of lubrication system generated heat to the airframe fuel tanks and the use of variable displacement fuel pumps or returning excess pump fuel to the air frame tanks are methods suggested as means of accomplishing this reduction.

Combustor Liner Heat Load Production Combustors

The impact on the performance and the operating characteristics of reference engine combustion systems operating with combustor operating on broad property fuels without incorporating design modifications was considered as the first study case in the analytical program.

It was noted as a result of data obtained from a literature survey that an increase in the aromatics content of the fuel had a substantial impact on the liner temperatures (ref. 2). This was attributed to increased concentrations of highly luminous carbon particles in the combustion gases with the increased aromatic content. This phenomenon is stated to be most significant in the combustion zone where the local fuel/air ratio, particulate concentrations, and gas temperatures are highest.

A change in fuel aromatic content corresponding to the change from Jet A to the broad property fuel was predicted to produce a 10 to 50°K increase in liner temperature for existing production combustors. The higher liner temperatures experienced by using the broad property fuel can be reduced to levels encountered with Jet A by increasing liner cooling airflows; however, to accomplish this, The P&WA Study (ref. 2) predicted that, for the JT9D-7F production combustor, the total fraction of combustor air used for cooling would have to be increased to nearly 70 percent of the total combustor airflow. It is predicted that this increase of cooling air could adversely affect combustion stability due to an altered recirculating flow structure in the primary zone, and also that ignition could be adversely affected because fuel dispersion into the vicinity of the ignitor could be inhibited. Data obtained from JT9D combustor tests indicate that increased cooling flow and decreased dilution flow seriously compromise the ability to control pattern factor. Also, the additional cooling air has a quenching effect on reactions, with a resulting increase in low power emissions.

Advanced Combustor Concepts

As the result of test data obtained from the literature the analytical studies predicted that liner temperatures of advanced combustors designed to produce low emissions levels were less sensitive to changes in fuel composition than production combustor. This was attributed to the fact that the advanced combustors were designed for lean combustion zone equivalence ratio in order to produce lower NO_x values and consequently they operated at lower flame temperatures than the production combustors and as a result produced lower liner temperatures.

Combustor Pollutant Emissions And Smoke

Exhaust emissions levels, using Jet A fuel and the broad properties ERBS fuel, were estimated for the production engine and the E^3 conceptual combustor designs. The emissions levels, expressed as emission indicies for the cruise and takeoff cycle for GE and for the takeoff cycle for P&WA and as the maximum smoke number at the takeoff condition for GE and P&WA, are presented in Table IV-1 and V-1 for the production engine combustor concepts and in Table IV-11 and V-11 for the E^3 combustor concepts. Correction factors for the CO, HC, NO_x and smoke emissions, using broad property fuel, were calculated using the emissions correlations for broad property fuels obtained from the literature (ref. 1 & 2). For each of the pollutants and for each combustor concept, the emission levels, using the broad property fuel, are predicted to range from 4 to 12% higher than the emission levels with Jet A fuel. Although in general, this increase in emission levels is attributed to the lower hydrogen content and higher final boiling point of the broad property fuel, results obtained in reference 2 predicted this increases in carbon monoxide and unburned hydrocarbon emission level maybe attributable to variation in fuel atomization as opposed to variation in fuel chemistry.

In the GE study emission estimates for the E^3 baseline single annular CF6-50 and E^3 short single annular, annular slot, and variable geometry concepts are based on CFM6 engine test results, modified, as appropriate, for residence time, rich or lean burning conditions, dome velocity, and cycle conditions. The emission estimates for the CF6-50C and E^3 double annular and radial/axial concepts are based on the NASA/GE ECCP test results for the ECCP Phase II double annular and radial/axial combustion systems.

In the P&WA study, the emission results for the JT9D-7F and E^3 are based on the NASA/P&WA ECCP test results for ECCP Phase II vorbix and the premixed-prevaporized combustion systems.

The emission indicies for the E^3 combustor concepts are generally lower than those for the production engine combustor concepts.

Also, the E^3 smoke numbers are much less than those for the production engine. The E^3 is a mixed-flow engine system; the fan flow mixes with the core engine flow ahead of the exhaust nozzle, and the smoke from the core engine is diluted by the much larger fan stream. The production engines are separated-flow engines, and the smoke numbers for these engines are for the unmixed core engine flow.

Experimental Study

Contractor and Engine Selection

The General Electric Company Aircraft Engine Group was selected to conduct the experimental part of the study through a competitive procurement procedure. This study was conducted at the GE facilities at Evendale, Ohio. The contract duration was twelve months.

The engine used as the reference engine in this study was the CF6-50C engine. Operating conditions for this engine are contained in Table I.

General Electric Aircraft Group Experimental Combustor Designs

The engine selected as the reference engine for the NASA/General Electric Experimental study is the CF6-50C engine. The combustion systems evolved and evaluated for this engine were designed to incorporate improved primary combustion zone designs that can satisfactorily accomodate Broad Property Fuels. Testing was conducted in two phases in the 36-degree sector CF6-50C combustor test rig (fig. 1). The current combustor configuration and three advanced double annular combustor concepts specifically designed to provide improved smoke and carbon formation suppression were evaluated in the initial screening phase of the program. These combustor designs are shown in fig. 2. The design concept demonstrating the most promise for meeting study goals was subjected to additional evaluation in a parametric investigation.

Baseline Combustor

The GE CF6-50C engine production combustor configuration presented in fig. 2. was used as the baseline combustor.

Advanced Designs

The three advanced double annular combustor concepts, illustrated in Figure 2, consisted of (1) a concept employing high pressure drop fuel nozzles for improved atomization, (2) a concept with premixing tubes in the main stage, and (3) a concept with the pilot stage on the inside and the main stage on the outside which is the reverse of the other two concepts.

Configuration 1

The first advanced combustor concept, the double annular combustor configuration 1, shown in Fig. 2, has the pilot dome in the outer annulus outside with the main or high power stage in the inner annulus. Each dome employs thirty swirlers, which are adaptations of designs developed during the Quiet Clean Short Experimental Engine (QCSEE) Program (ref. 10). Thirty air atomizing fuel nozzles are used incorporating high pressure air to produce a very finely atomized fuel spray.

Configuration 2

Configuration 2 shown in Fig. 2 employs premixing of the main stage fuel. In this design, the pilot is situated on the out-board side as in Configuration 1 and thirty counter-rotating swirl cups are employed. Conventional pressure atomizing fuel injectors are employed in the pilot. The main stage has thirty tubular pre-mixing ducts which provides approximately 2 milliseconds (ms) residence time for mixing and prevaporization of the fuel and air mixture. Single-stage pressure atomizing injectors and 15° swirlers are used to provide atomization and rapid mixing of the fuel and air at the forward end of the prevaporizing ducts. Counter-rotating swirlers of approximately 35° swirl angle are located at the junction of the premixing ducts and the dome to add additional air and mixing. The equivalence ratio of the mixture in the main stage dome is between 0.5 and 0.6 at high power design point conditions.

Configuration 3

Configuration 3, shown in Figure 2, features reversed main and pilot stages, with the main stage outboard of the pilot. Also, the main stage has been shortened. Some of the reasons for this arrangement include:

- reduced main stage residence time for minimum NO_x production.
- quenching of the pilot stage gases by the main stage unfueled air at low power conditions is prevented (sheltered pilot zone).
- the liner cooling is reduced because of reduced surface area
- the expected discharge gas temperature profile will more nearly match the required turbine profile.

In this design thirty QCSEE type counter-rotating swirlers are employed in both the pilot and main stage. Also, both stages use pressure atomizing fuel injectors.

Because the main stage dome has been moved aft, cooling air required for the outer liner and for one side of the center body has been reduced. This air is used for dilution at the aft end of the liner for better pattern factor and profile trim. This minimizes turbine cooling requirements.

Test Fuels

In the experimental phase of the study 14, 13, and a 12% hydrogen fuel blend was used as the test fuel. The current combustion characteristics of Jet A are controlled by aromatics content (25 percent maximum), smoke point (18 minimum), and naphthalene content (3 percent maximum). However, present plans are considering the replacement of one or more of the above controls by a minimum-hydrogen content, which is regarded as a more precise and significant measurement. Average Jet A today, has a hydrogen content of 13.8 percent. The broad property fuel was targeted to a substantially lower but still realistic level, and was established at 12.8 percent.

The low-temperature properties of Jet A are controlled by the freezing point (233K maximum) and the viscosity at 253K (8 mm^2/s maximum). The corresponding values established for the broad property fuel were: freezing point, 244K maximum; and viscosity at 253K 12 mm^2/s maximum. The specifications for these fuels are presented in reference 3.

Experimental Test Facility and Test Procedure

A total of four combustor configurations were tested, including the production combustor. A sketch of each configuration is shown in Fig. 2. The production CF6-50C combustor was tested to provide baseline data. One test of each of the three advanced combustor concepts was conducted for screening to determine the most promising. An additional parametric test was conducted with the most promising combustor. For a complete analysis of the data, see the final report of the program, reference 4.

Experimental Combustor Test Results

The baseline CF6-50C burner was tested first. The baseline test showed that smoke and CO levels for these sector tests were somewhat higher than for full annular tests because of leakage in the rig, however trends with operating conditions were as expected. Other test data were not affected. The baseline burner showed some sensitivity to fuel hydrogen content with regard to smoke, NO_x (takeoff), and liner temperatures.

Of the four burners tested, Concept 2 had the lowest NO_x levels, a very clean dome with virtually no carbon deposits, lower smoke levels than the baseline combustor, very low dome temperatures and no combustion instability in the inner liner downstream of the premixing tubes. This concept exhibited hot streaks on the liner down stream of the premixing tubes. It is anticipated however, that this liner temperature problem would be relatively easy to remedy by the use of hole pattern adjustments and preferential cooling. Therefore these high temperatures were not considered a major problem.

Concept 1 produced low smoke levels and showed little sensitivity to fuel hydrogen content with regard to smoke levels and metal temperatures. NO_x levels were lower than CF6-50C levels but higher than Concept 2 levels. These levels were higher than expected for this design based on previous tests of similar designs in the Experimental Clean Combustor Program. It is suspected that these results were due to the loss of some Nichrome patches on dilution holes which adversely affected combustor airflow distribution. The liners were made from CF6-50C combustors.

Concept 3 produced the lowest smoke levels and demonstrated that the radial temperature profile could be inverted by reversing the pilot and main stage domes in a double annular combustor. It is believed that during a portion of the test with this concept the flame was not seated in the pilot dome as evidenced by very low metal temperatures. This design exhibited high resonance values and the flame was unstable. It is likely that the observed resonance and dome instability was influenced by leakage between the three-cup sector and the test rig side walls. Because of combustion stability problems, this combustor yielded high CO and some liner temperature data which are not believed representative of this concept's potential, and thus these data are omitted in the following figures. It is believed that a complete set of representative data was obtained for Jet A fuel.

Concept 2 demonstrated the potential of a premixed-prevaporized design in achieving low NO_x levels and clean liners and domes. The Concept 1 test showed that high pressure drop (ΔP) fuel nozzles gave no significant improvement over the low ΔP fuel nozzles tested earlier in similar combustor designs. Data from the Concept 3 test were considered not representative of the concept's potential because of combustion stability and resonance problems. Thus Concept 2 was chosen for the parametric test. Although no refinement or development tests to resolve problems were conducted on these advanced designs, they all appear to have potential for use with fuels with broadened specifications. Dome temperatures for all of the three advanced designs were extremely low and showed essentially no effect of fuel type whereas for the baseline combustor, dome temperatures were higher with reduced fuel hydrogen content. These results are illustrated in Figure 3.

Liner temperatures also tended to exhibit reduced sensitivity to fuel hydrogen content for the advanced designs. Figure 4 shows trends of liner temperature as a function of fuel hydrogen content relative to temperatures measured using Jet A fuel. As is shown, the lowest temperatures were not obtained with the premixed system (Concept 2). Previous experience with double annular combustors, including a premixed system (NASA/GE Experimental Clean Combustor Program), would lead one to expect less sensitivity for a premixed system than for a double annular combustor. It is theorized, therefore, that the fuel-air mixture at the premixing tube exit was not as uniform as desired and that this lack of uniformity influenced the liner temperature results.

Carbon deposits in the dome regions were also significantly reduced with the advanced domes. Figure 5 shows the baseline combustor post test dome conditions. A light coating of soot is evident on a large portion of the dome surface and some buildup occurred on the swirl cup venturi trailing edges. All three of the advanced designs had relatively little carbon on the pilot dome surfaces. Concepts 1 and 3 had some carbon on the main stage dome surfaces. Concept 2, with the premixed main stage, had virtually no carbon on the dome as shown by Figure 6. It should be noted that all of the advanced designs had prototype fuel nozzles that had a bluff region between the fuel nozzle and swirl cup. These bluff regions, which would be eliminated in product engine designs, had carbon deposits.

Smoke data exhibited the expected trend toward generally increased smoke with reduced hydrogen content. Concept 2, with the premixing dome, had higher smoke levels than the other two advanced designs. This finding is also believed to be the result of less than uniform fuel-air mixtures at the exit of the premixing duct. Concept 3 had the lowest smoke levels measured; Concept 1 also had low smoke levels and showed the least sensitivity to fuel type. Figure 7 presents some of the smoke data correlations for the four combustor configurations at simulated takeoff conditions.

Only general trends for radial exit temperature profiles are obtainable in sector combustor tests. However, it appears that Concept 3 with the inverted main to pilot stage shifted the profile in the desired direction. For Concept 1 with the main stage on the inboard side, the profile was peaked at approximately 40% of the radial exit height (peaked inboard). For Concept 3 with the main stage on the outboard side, the profile was peaked at approximately 60% of the exit height.

All of the advanced designs appear to have the potential for low NO_x levels. The increased pressure loss nozzles used in Concept 1 did not provide reduced NO_x relative to earlier full annular tests of double annular combustors (NASA/GE Experimental Clean Combustor Program) although these results were clouded by the liner hardware problems previously mentioned. Concept 3 provided slightly lower NO_x levels than Concept 1, apparently due to its reduced main stage residence time. Concept 2, the premixed main stage design, had the lowest NO_x levels and the lowest NO_x sensitivity to fuel hydrogen content, as shown in Figure 8.

The advanced concepts all had higher CO levels than the baseline combustor. This is as expected, based on previous tests, and is attributed to the lean dome operation of these designs. At idle conditions the advanced designs would all have very low CO levels since only the pilot stages would be in operation. Fuel hydrogen content was not found to have a strong effect on CO emissions as shown in Figure 9.

Combustor Performance Trends Observed in the Comparison of Analytical and Experimental Studies

The analytical study predicted that the increase liner heat load produced by broad property fuel in production combustors will cause an increase in liner temperature resulting in deterioration in the life of the liner. P&WA predicted an increase in liner temperature of 18 to 40°K at takeoff power while GE predicted somewhat lower values when a broad properties fuel is substituted for Jet A. The experimental data indicated that the liner temperature increase 35°K on the dome and approximately 65°K on the hottest location on the liner in the production combustor at cruise condition for changing similar fuels as those used in the analytical program.

As predicted in the analytical study the use of broad properties fuel in the experimental study resulted in an increase in smoke and NO_x production at all power levels and caused increased carbon monoxide and unburned hydrocarbon emissions at low power levels.

Concluding Remarks

The analytical and experimental efforts described in this paper represent a part of a comprehensive program being conducted at the NASA Lewis Research Center aimed at defining the performance and environmental impacts associated with the usage of broad property fuels for commercial and general aviation aircraft applications. Additional research and technology efforts, currently in progress, are further assessing the short-term impacts of broad property fuel usage on current aircraft systems, exploring modifications to current systems which could lessen the impacts of broad property fuels, and evolving advanced fuel systems and combustors optimized for broad property fuel usage. Future program activities are planned to investigate long-term and transient performance effects with these fuels.

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TABLE 1-1 - G.E. CF6-50C Combustor Operating Conditions

	Idle	Approach	Climb	Takeoff	Maximum* Cruise
Percent of takeoff power	6.0	30.0	85.0	100.0	N.A.
Inlet total pressure - Atm.	4.13	11.84	25.78	29.46	11.90
Inlet total temperature - K	477	631	791	826	738
Exit total temperature - K	857	1135	1523	1615	1495
Total combustor airflow - kg/sec	19.3	48.1	90.7	101	42.3
Fuel-air ratio - g/kg	9.5	13.4	21.1	23.2	21.9
Compressor exit velocity - m/sec	129	149	160	160	149

*Maximum Cruise at 10,670 m, 0.85 Mach No.

TABLE 1-2 - G.E. E^3 Combustor Operating Conditions

	Idle	Approach	Climb	Takeoff	Maximum* Cruise
Percent of takeoff power	6.0	30.0	85.0	100.0	N.A.
Inlet total pressure - Atm.	4.05	11.84	26.00	29.80	12.93
Inlet total temperature - K	488	635	786	819	757
Exit total temperature - K	943	1137	1528	1617	1531
Total combustor airflow - kg/sec	9.66	25.8	49.0	54.9	24.5
Fuel-air ratio - g/kg	11.5	13.3	21.5	23.6	22.5
Compressor exit velocity - m/sec	127	151	161	163	156

**Maximum Cruise at 9144 m, 0.80 Mach No.

TABLE II-1 - P&WA JT9D-7F Combustor Operating Conditions

	Idle	Approach	Climb	Takeoff	Maximum* Cruise
Percent of takeoff power	6.7	30.0	85.0	100.0	N.A.
Inlet total pressure - Atm.	3.65	8.84	19.5	223	9.7
Inlet total temperature - K	447	582	735	767	701
Exit total temperature - K	861	1150	1502	1595	1447
Total combustor airflow - kg/sec	20.74	42.04	53.09	89.00	41.64
Fuel-air ratio - g/kg	10.9	15.6	22.6	24.8	21.7
Compressor exit velocity - m/sec	108	117	129	152	126

*Maximum Cruise at 10,666 m, 0.8 Mach No.

TABLE II-2 - NASA/P&WA E^3 Combustor Operating Conditions

	Idle	Approach	Climb	Takeoff	Maximum* Cruise
Percent of takeoff power	6.0	30.0	85.0	100.0	N.A.
Inlet total pressure - Atm.	3.97	11.82	27.52	31.67	13.83
Inlet total temperature - K	488	620	780	812	755
Exit total temperature - K	925	1106	1510	1602	1533
Total combustor airflow - kg/sec	10.69	29.85	5751	64.18	28.78
Fuel-air ratio - g/kg	11.8	13.7	21.7	23.8	23.1
Compressor exit velocity - m/sec	122	142	151	153	126

*Maximum Cruise at 10,668 m, 0.80 Mach No.

TABLE III. SUMMARY OF EACH ANALYTICAL COMBUSTOR CONCEPT DESIGN

A. G.E. CF6-50 PRODUCTION ENGINE COMBUSTORS

CONCEPT 1: Baseline CF6-50 Single Annular production combustor.

CONCEPT 2: Counterrotating swirlers are installed in the dome and impingement cooling is used for the combustor liner.

CONCEPT 3: Circumferential row of premixing ducts are used in the dome, two sets of swirl vanes concentric with premixer swirlers are employed.

CONCEPT 4: Two concentric burning zones are separated by annular centerbody.

CONCEPT 5: Two combustion stages an upstream pilot stage and an axially displaced mainstage are used.

CONCEPT 6: Premixer cylindrical ducts containing variable swirl vanes that are concentric with fuel injectors are located in the dome region of the combustors.

B. P&WA JT9-7 PRODUCTION ENGINE COMBUSTORS

CONCEPT 1: Baseline JT9D-7 single stage production combustor.

CONCEPT 2: Vorbix two stage combustor-pilot stage and axially displaced mainstage.

CONCEPT 3: Premix Prevaporized two burning zones with premixing of the fuel and air prior to injection in each zone.

C. NASA/G.E. ENERGY EFFICIENT ENGINE COMBUSTORS

CONCEPT 1: Based on most recent G.E. combustor design technology combustion system length is reduced from the baseline design.

CONCEPT 2: The length is 3/4 that of the production combustor design.

CONCEPT 3: Similar to the production engine design, except combustor system length reduced.

CONCEPT 4: The combustor system length is reduced from the production combustor design.

CONCEPT 5: Similar to the production engine radial/axial combustor design, except a parallel row of cylindrical tube is used for the premixing duct.

CONCEPT 6: Similar to the production engine design, except combustor system length is reduced.

D. NASA/P&WA ENERGY EFFICIENT ENGINE COMBUSTORS

CONCEPT 1: Baseline JT9D-7 bulkhead front end with reduced combustion system length.

CONCEPT 2: Vorbix - Throat restriction between pilot and high power stage eliminated - reduce combustor system length.

CONCEPT 3: Premixed prevaporized - reduced combustion system length.

TABLE IV-1 - SUMMARY OF COMBUSTOR EMISSIONS PREDICTIONS

Emission Indices gm/Kg

G.E. CONCEPTUAL CF6-50C COMBUSTORS		CO	HC	NOx	MAX. SMOKE
(A) JET A FUEL					
BASELINE SINGLE ANNULAR	(A)*	0.20	0.01	36.5	12.0
	(B)**	2.60	0.01	17.8	
SHORT LENGTH SINGLE ANNULAR	(A)	0.20	0.01	20.9	20.6
	(B)	1.00	0.01	10.4	
ANNULAR SLOT WITH PREMIXING	(A)	0.30	0.01	21.7	14.3
FUEL INJECTION	(B)	1.20	0.01	10.9	
NASA/GE ECCP DOUBLE ANNULAR	(A)	0.10	0.01	18.5	10.0
	(B)	0.30	0.30	8.4	
NASA/GE ECCP RADIAL/AXIAL	(A)	3.70	0.10	18.5	10.0
	(B)	21.7	0.10	8.4	
PREMIXING, PREVAPORIZING	(A)	0.20	0.01	7.70	10.0
VARIABLE GEOMETRY	(B)	1.00	0.01	3.90	

(B) BROAD PROPERTY FUEL					
BASELINE SINGLE ANNULAR	A	0.22	0.01	38.0	13.0
	B	2.91	0.01	18.5	
SHORTLENGTH SINGLE ANNULAR	A	0.22	0.01	21.8	22.0+
	B	1.12	0.01	10.8	
ANNULAR SLOT WITH PREMIXING	A	0.34	0.01	22.6	15.5
FUEL INJECTION	B	1.34	0.01	11.4	
NASA/GE ECCP DOUBLE ANNULAR	A	0.11	0.01	19.3	11.0
	B	0.34	0.01	8.8	
NASA/GE ECCP RADIAL AXIAL	A	4.10	0.11	19.3	11.0
	B	24.3	0.11	8.8	
PREMIXING, PREVAPORIZING	A	0.22	0.01	8.02	11.0
VARIABLE GEOMETRY	B	1.12	0.01	4.06	

* A - Takeoff Condition

**B - Cruise Condition

TABLE IV-2 - SUMMARY OF COMBUSTOR EMISSIONS PREDICTIONS

Emission Indices gm/Kgm

G.E. CONCEPTUAL E^3 COMBUSTORS		CO	HC	NOx	MAX. SMOKE
(A) JET A FUEL					
BASELINE SINGLE ANNULAR	A*	0.20	0.01	26.6	1.7
	B**	0.80	0.01	14.2	
SHORT LENGTH SINGLE ANNULAR	A	0.30	0.01	20.5	4.9
	B	1.20	0.01	10.9	
ANNULAR SLOT WITH PREMIXING	A	0.20	0.01	21.1	2.9
FUEL INJECTION	B	0.80	0.01	11.1	
NASA/GE ECCP DOUBLE ANNULAR	A	0.10	0.01	17.5	1.2
	B	0.30	0.01	9.3	
NASA/GE ECCP RADIAL/AXIAL	A	3.70	0.10	17.5	1.2
	B	16.5	0.10	9.3	
PREMIXING, PREVAPORIZING	A	0.20	0.10	7.5	
VARIABLE GEOMETRY	B	0.76	0.01	4.0	1.2
(B) BROAD PROPERTY FUEL					
BASELINE SINGLE ANNULAR	A	0.22	0.01	27.7	1.8
	B	0.90	0.01	14.8	
SHORTLENGTH SINGLE ANNULAR	A	0.34	0.01	21.4	5.3
	B	1.34	0.01	11.4	
ANNULAR SLOT WITH PREMIXING	A	0.22	0.01	22.0	3.2
FUEL INJECTION	B	0.90	0.01	11.6	
NASA/GE ECCP DOUBLE ANNULAR	A	0.11	0.01	18.2	1.3
	B	0.34	0.01	9.70	
NASA/GE ECCP RADIAL AXIAL	A	4.14	0.11	18.2	1.3
	B	18.5	0.11	9.7	
PREMIXING, PREVAPORIZING	A	0.22	0.01	7.82	1.3
VARIABLE GEOMETRY	B	0.85	0.01	4.17	

*A - Takeoff Condition

**B- Cruise Condition

TABLE V-1 - SUMMARY OF COMBUSTOR EMISSIONS PREDICTIONS

Emission Indicies gm/Kg

Takeoff Condition

P&WA CONCEPTUAL JT9D COMBUSTORS	CO	HC	NOx	MAX. SMOKE
(A) JET A FUEL				
SINGLE STAGE	0.4	0.3	42.4	4
VORBIX	1.0	0.2	13.0	30
PREMIX-PREVAPORIZED	0.7	0.4	7.88	--
(B) BROAD PROPERTY FUEL				
SINGLE STAGE	0.4	0.3	48.3	4.6
VORBIX	1.0	0.2	13.0	30

TABLE V-2 - SUMMARY OF COMBUSTOR EMISSIONS PREDICTIONS

Emission Indicies gm/Kgm

Takeoff Condition

P&WA CONCEPTUAL E^3 COMBUSTORS	CO	HC	NOx	MAX. SMOKE
(A) JET A FUEL				
SINGLE STAGE	0.4	0.05	31.0	61
VORBIX	0.7	0.15	19.0	41
PREMIX-PREVAPORIZED	0.3	0.3	13.8	--
(B) BROAD PROPERTY FUEL				
SINGLE STAGE	0.4	0.05	32.5	70
VORBIX	0.7	0.15	19.0	45

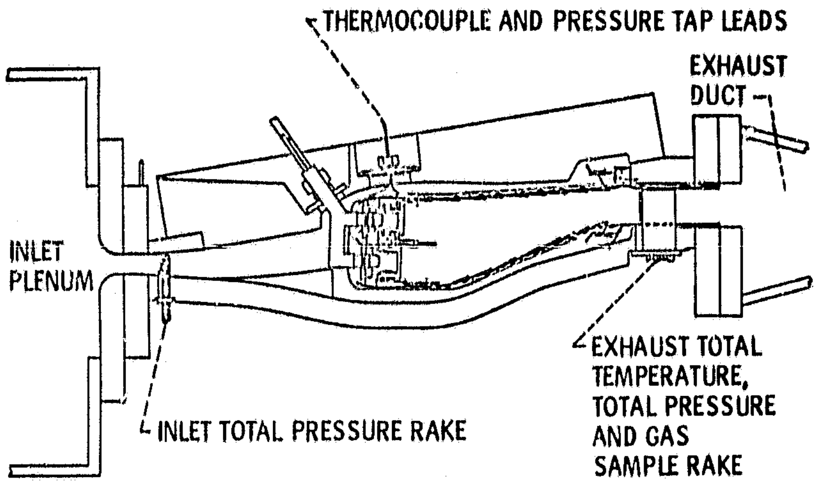


Figure 1. - Overall combustor test rig showing instrumentation location.

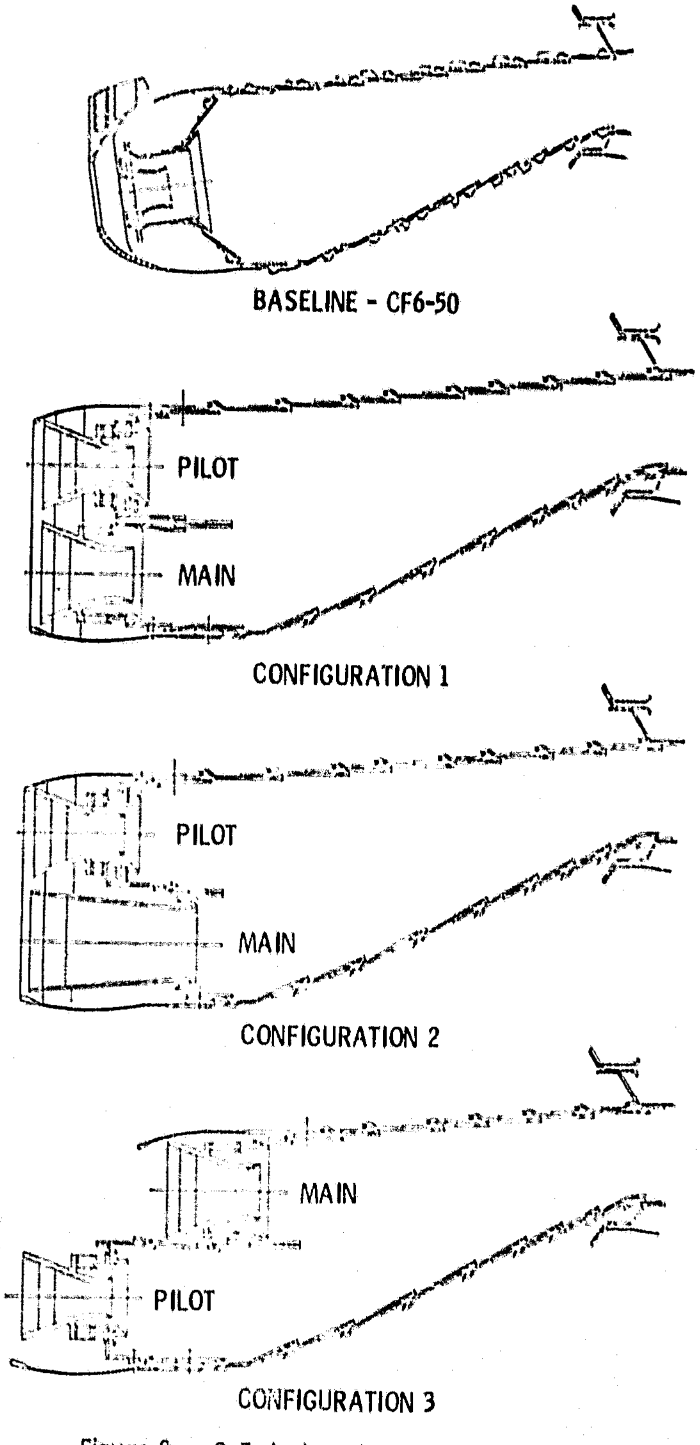


Figure 2. - G. F. test combustor configurations.

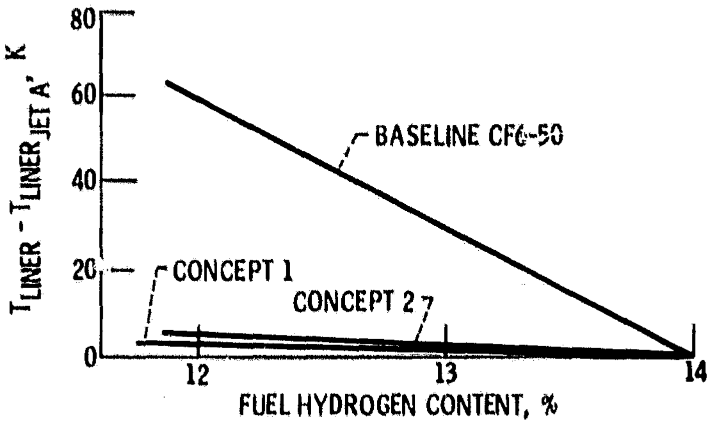
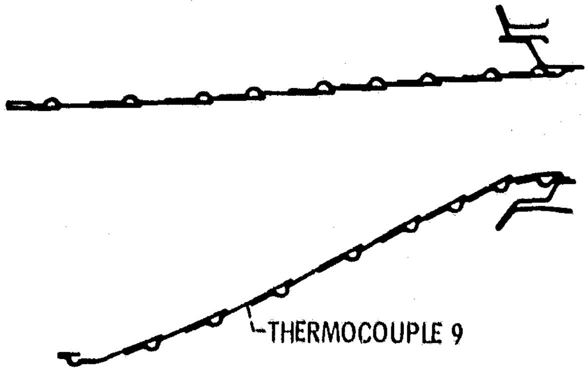


Figure 3. - Local dome temperature vs. fuel hydrogen content at true cruise conditions, f = 0.021. T/C located midway between main cup center.



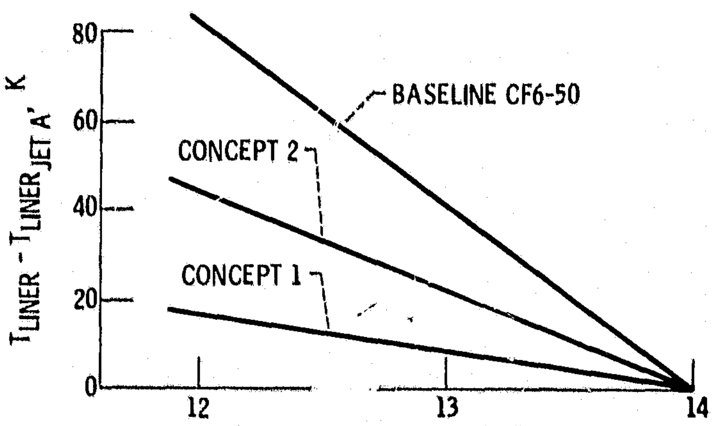


Figure 4. - Local liner temperature, thermocouple 9, vs. fuel hydrogen content, at true cruise conditions, f_2.

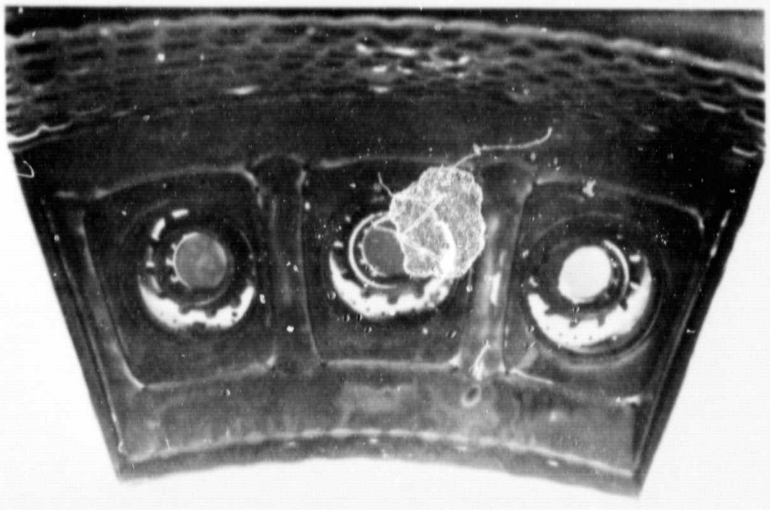


Figure 5. - Baseline CF6-50 dome after test.

C47511

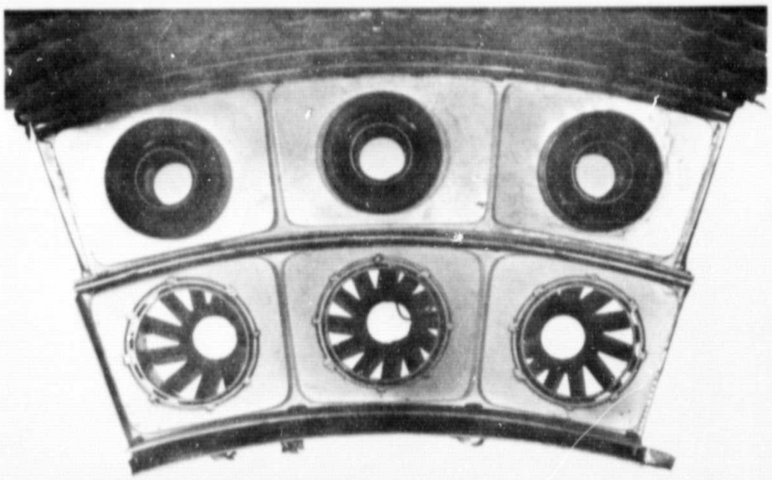


Figure 6. - Concept 2 dome after test.

C48136

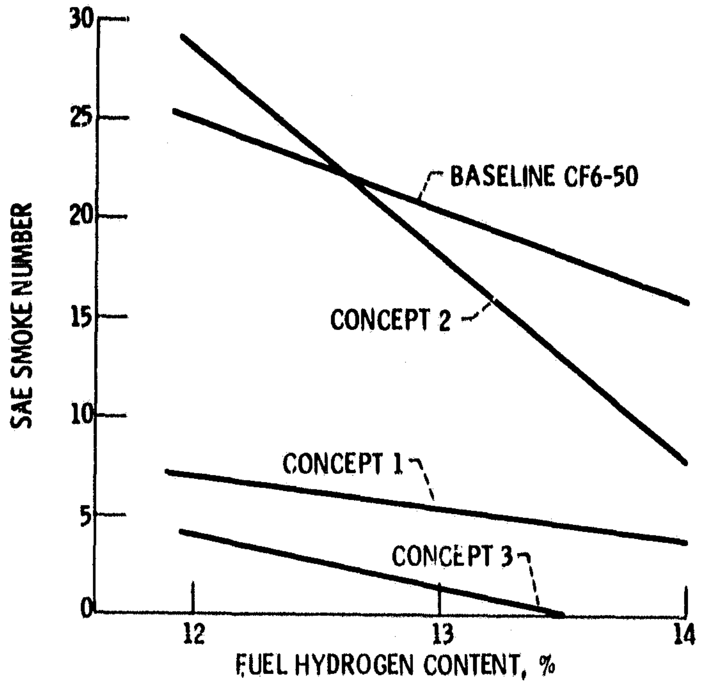


Figure 7. - SAE smoke number vs. fuel hydrogen content for the four combustor concepts tested, at simulated takeoff, f = 0.016.

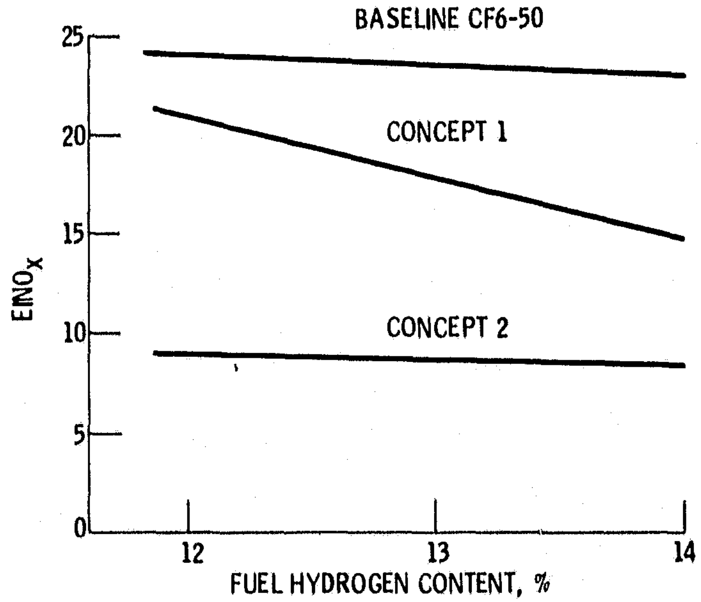


Figure 8. - NO_X emission index vs. fuel hydrogen content for three test combustors at true cruise conditions, f = 0.021.

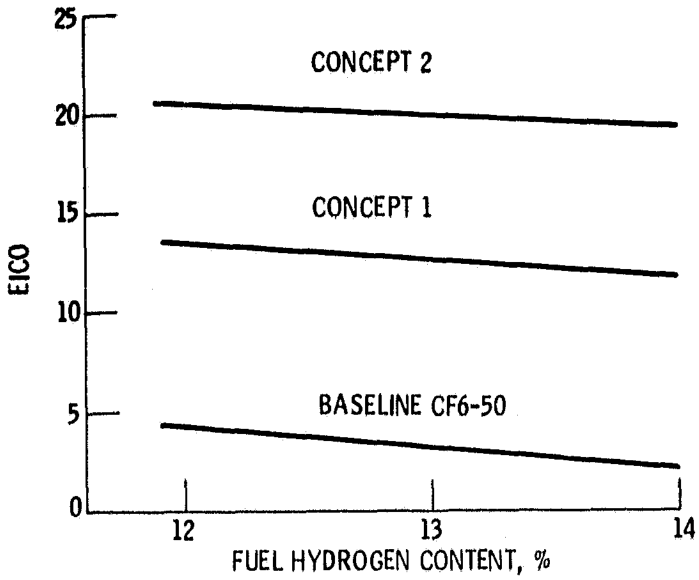


Figure 9. - CO emission index vs. fuel hydrogen content for three test combustors at true cruise conditions, f = 0.021.