EXPERIMENTAL COMBUSTOR STUDY PROGRAM

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The objective of this recently completed program was to evaluate the use of advanced combustor concepts as a means of accommodating possible future broad-specification fuels.

The combustor evaluations consisted of sector combustor tests, using a three-swirl cup sector CF6-50 test rig. The tests were conducted with a non-vitiated air supply and an on-line exhaust gas analysis system, as well as other normally used combustion testing control systems, instrumentation and data acquisition equipment.

The various combustor configurations were evaluated at true cruise and simulated takeoff (P_3 reduced from 2.96 MPa to 1.59 MPa) conditions for the CF6-50 cycle. In each test, the combustors were evaluated with three fuels:

- Jet A - 14% Hydrogen by weight
- ERBS - 13% Hydrogen by weight
- Special Blend - 12% Hydrogen by weight

The program included one test of a current production CF6-50 combustor configuration, Figure 1, to serve as a baseline for comparison, one test each of three advanced combustor concepts and a parametric test of the most promising of the three advanced concepts.

The three advanced double annular combustor concepts, which are also illustrated in Figure 1, 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. This last concept was intended to reduce the main stage length and, therefore, its residence time and NO_x emissions levels, and to provide an improved exit radial temperature profile. Double annular combustors, with the pilot on the outside, have shown tendencies in previous tests to have inboard-peaked temperature profiles.

The baseline CF6-50 burner was tested first. The baseline test showed that smoke and CO levels for sector tests would be somewhat higher than for full annular tests because of leakage in the rig; however, trends with operating conditions were as expected. Other test data would not be 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 at any operating condition. Liner temperatures were low except for a region on the inner liner downstream of the premixing tubes. 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 CF6-50 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 CF6-50 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. The NO_x levels were between those measured for the other two concepts. However, this combustor encountered combustion resonance and dome flame stability problems at some operating conditions. It is believed that during a portion of the test the flame was not seated in the pilot dome as evidenced by very low metal temperatures. It is likely that the observed resonance and dome instability were 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 this data is 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 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 was 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 2.

Liner temperatures also tended to exhibit reduced sensitivity to fuel hydrogen content for the advanced designs. Figure 3 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 possible. 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 4 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 5. 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 6 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 30% 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 ΔP 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 least NO_x sensitivity to fuel hydrogen content, as shown in Figure 7.

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 8.

Concluding Remarks

All of the advanced concepts show promise for reduced sensitivity to fuel hydrogen content. Some hardware problems were encountered, but these problems could be quickly resolved if refinement tests were conducted.

The design with the premixing main stage was selected for the parametric test because of its low NO_x emissions level, carbon free dome and very low dome temperatures which were essentially independent of fuel type. The other advanced designs also had low dome temperatures. The premixing dome design liner temperatures exhibited less sensitivity to fuel type than did the baseline combustor, although more sensitivity than observed for Concept 1. The inner liner hot spot and the observed smoke results for the premixing design suggest that the fuel-air mixture was not as uniform as desired. Additional work with premixing dome designs is recommended.

The Concept 3 double annular combustor with the two domes reversed indicated an improved exit temperature profile. One possible alternative design would be Concept 3 with a premixing dome.

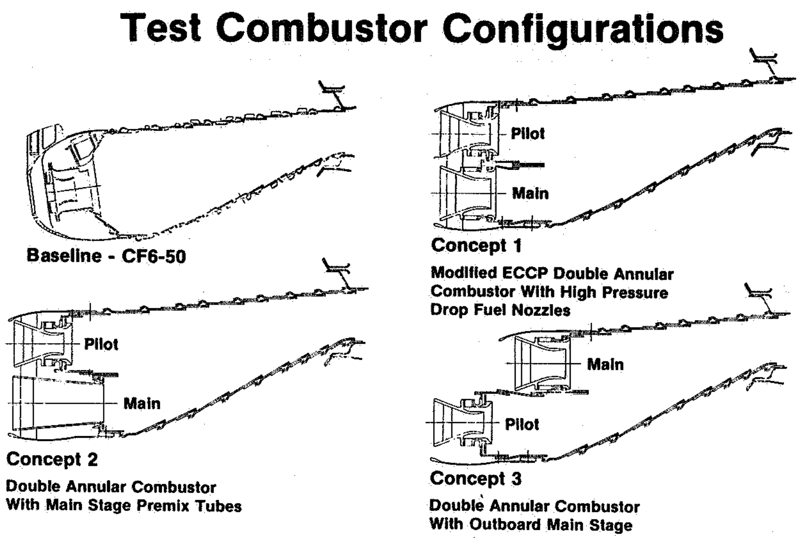

FIGURE 1

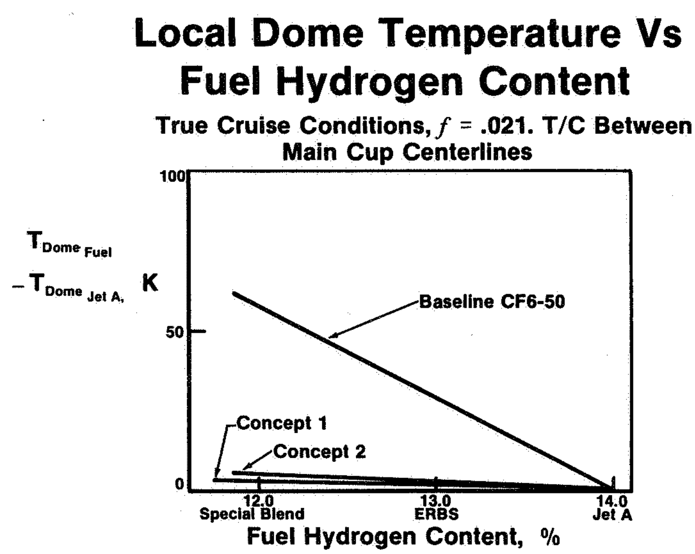

FIGURE 2

Local Liner Temperature Vs Fuel Hydrogen Content

True Cruise Conditions, f = .021

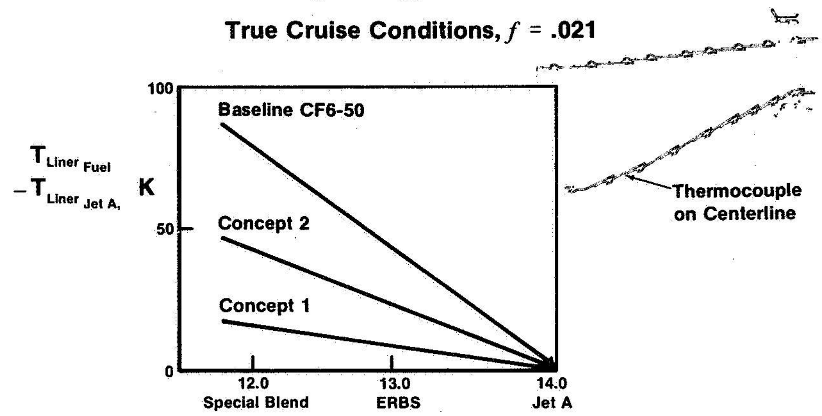

FIGURE 3

Baseline CF6-50 Dome After Screening Test

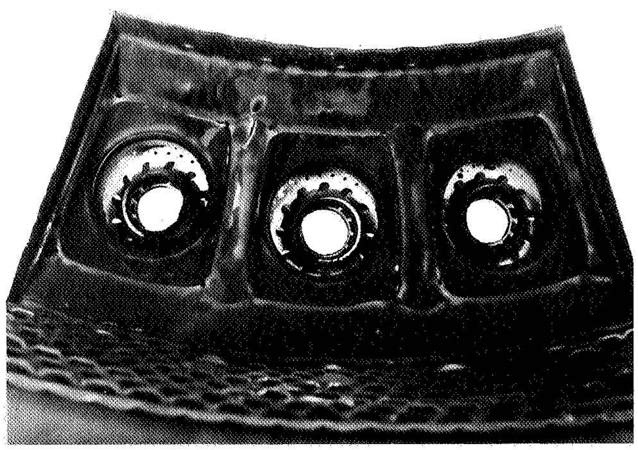

FIGURE 4

Concept 2
Dome
After
Parametric
Test

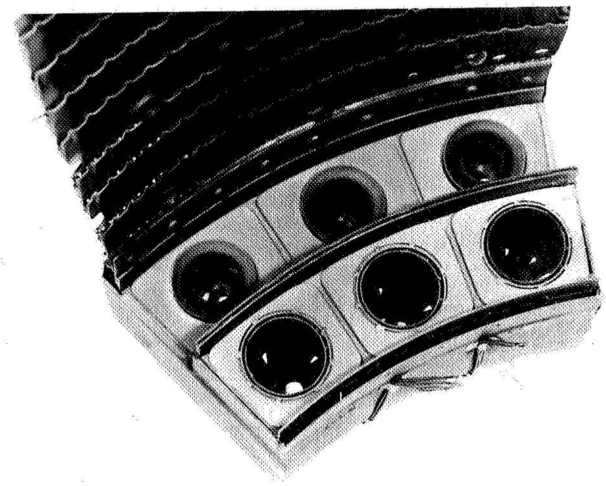

FIGURE 5

SAE Smoke Number Vs Fuel Hydrogen Content

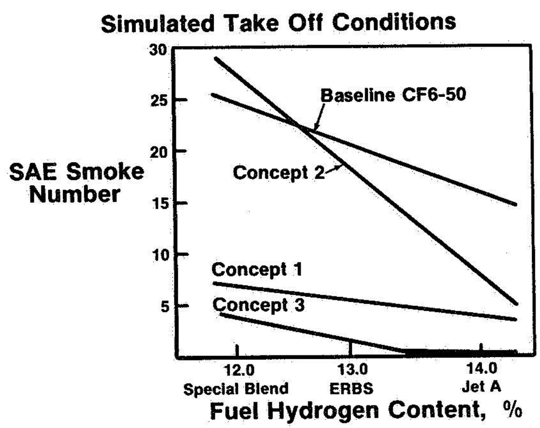

FIGURE 6

NO_x Emission Index Vs Fuel Hydrogen Content

True Cruise Conditions, f = .016.

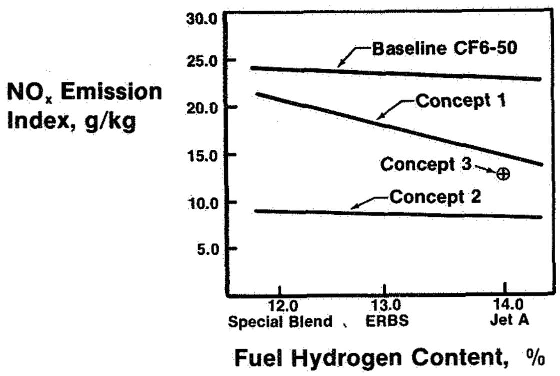

FIGURE 7

CO Emission Index vs Fuel Hydrogen Content

True Cruise Conditions, f = .016

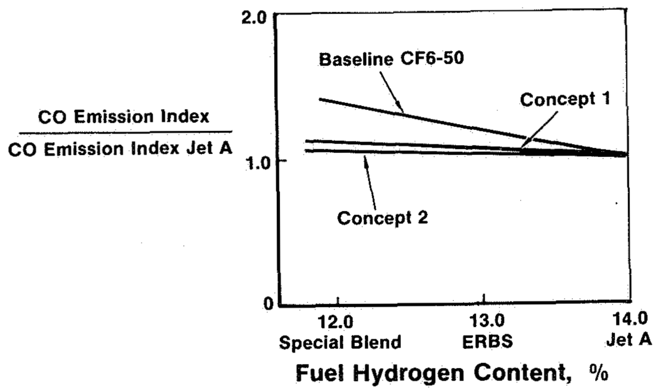

FIGURE 8