# ADVANCED LOW EMISSIONS CATALYTIC COMBUSTOR PROGRAM (ALECC)

## PHASE 1 - DESIGN STUDY


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## INTRODUCTION

The Advanced Low Emissions Catalytic Combustor Program (ALECC) is being undertaken to evaluate the feasibility of employing catalytic combustion technology in aircraft gas turbine engines as a means to control emission of oxides of nitrogen during subsonic stratospheric cruise operation. The ALECC Program is being conducted in three phases, as illustrated in Table I. The first phase, which was completed in November, 1978, consisted of a design study to identify catalytic combustor designs having the greatest potential to meet the emissions and performance goals specified in Table II. The primary emissions goal of this program was to obtain cruise $NO_x$ emissions of less than 1g/kg (compared with levels of 15 to 20 g/kg obtained with current designs). However, good overall performance and feasibility for engine development were heavily weighted in the evaluation of combustor designs. The General Electric design effort was supported by a subcontract with Engelhard Industries, specialists in the catalytic combustion field.

## Catalytic Combustor Design Considerations

Reference Engine Operating requirements are compared with projected catalyst performance in Table III. Performance projections in this table were based on Engelhard Industries estimates of catalyst development over a 5 to 10 year period.

It is apparent that the catalyst cannot cover the entire range of operation. Specifically, idle inlet temperature is not high enough for catalyst ignition, and exit temperatures at the idle, approach, and minimum cruise conditions are too low to obtain high combustion efficiency.

Catalyst combustion efficiency characteristics as a function of fuel/air ratio(at constant inlet conditions) are shown in Figure 1. In order to obtain efficiency above 99.9%, the fuel/air ratio must be high enough to assure operation in the catalytically supported homogeneous combustion mode. Also shown in Figure 1 is the maximum fuel/air ratio corresponding to the catalyst maximum use temperature. In order to obtain high efficiency and avoid exceeding the catalyst maximum use temperature at the conditions shown, the mixture entering the catalyst must be between fuel/air ratios of about 24 and 35 g/kg. This provides for about ±20% spacial variation in mixture uniformity if average fuel/air ratio is exactly 29.5 g/kg. However, in practice, mixture uniformity within about ±10% will be required to allow some margin for fuel injector deterioration and control system inaccuracy.

Obtaining a uniform, fully evaporated fuel/air mixture is complicated by autoignition considerations. Autoignition delay times predicted based on References 1-3 are between 9.6 and 16.1 ms at the maximum cruise conditions, decreasing to between 2.2 and 3.1 ms at hot day takeoff. Within this period fuel must be injected, evaporated and thoroughly mixed with the air stream.

Principal catalytic combustor design considerations and possible design solutions are summarized in Table IV.

## Combustor Conceptual Design

The six catalytic combustor conceptual designs are shown in Figures 2-7. All of these concepts incorporate (1) a conventional pilot stage designed specifically for relight and low idle emissions, and (2) a lean premixed catalytic stage sized specifically for ultralow $NO_x$ emissions at cruise.

Concept 1(Figure 2) is a basic series staged combustor design. At power levels up to about 25% of rated thrust, only the pilot stage is fueled, and the catalyst is used as a cleanup device. At power levels above 25%, the pilot stage is cut back and fuel is injected through multiple point injectors located in the 90 main stage mixing chutes. This fuel is atomized by, and mixed with approximately 40% of combustor airflow which also passes through the chutes. During intermediate power operation, sector fueling is used to control catalyst inlet fuel/air ratio. Combustor pressure drop with this combustor is between 5 and 6% at all operating conditions.

The cross-sectional area of this combustor is reduced at the plane of the mixing chutes to accelerate the pilot stream, improving the velocity profile at the fuel injection plane and increasing the fuel/air mixing length, which is limited by autoignition requirements. Immediately upstream of the catalyst, the flow is rapidly diffused to the velocity required to obtain acceptable conversion and pressure drop.

This series staged design provides good emissions reduction potential because all fuel is reacted in the catalyst at all operating conditions. However, a major problem with this design is obtaining uniform fuel/air mixtures and avoiding autoignition with the main stage fuel injector system. This design also suffers because of increased system length and the difficulty of cooling the fuel injector chutes.

Concept 2(Figure 3)is a series staged combustor which incorporates (1) variable geometry, (2) a folded pilot burner, (3) external fuel/air mixing chutes, and (4) a third combustion stage downstream of the catalyst. At low power operating conditions, the variable geometry vanes are closed and all fuel is burned in the pilot stage. At intermediate and high power conditions, the variable vanes are opened, and fuel is injected through multiple point injectors located in the mixing ducts. At takeoff conditions and during transients, the third fuel injector stage may be fueled to avoid catalyst over temperature. As in the basic series staged design, circumferential fuel staging is utilized for catalyst fuel/air ratio control during intermediate power operation.

The use of variable geometry in this concept allows catalyst pressure drop to be increased relative to the basic series staged design, and also increases the air flow admitted through the fuel injection chutes to about 70% of combustor air flow at cruise conditions. The use of external fuel injection chutes eliminates the chute cooling problem encountered with Concept 1, and the reverse flow pilot stage provides some length reduction relative to the basic series staged combustor. In the analysis of this design, it was determined that the takeoff stage shown in Figure 3 would not be required if combustor aft section film cooling flow was eliminated and used instead as catalyst air flow. Since the takeoff stage positioned at the catalyst exit was considered a high risk design feature, a revised design in which the takeoff stage was removed and the aft section was convectively cooled using turbine cooling air was considered in the final combustor evaluation.

The increased fuel injection chute air flow in this concept tends to decrease fuel/air mixing requirements relative to the basic series staged design. However, obtaining uniform catalyst inlet fuel/air mixtures without encountering autoignition still presents a difficult problem. Other problem areas with this design are increased idle pressure drop (10% vs. 5% at cruise), and additional mechanical design and operational complexity.

Concept 3 (Figure 4) is an annular, parallel-staged combustor. In this design, approximately 40% of the combustor air flow is used for pilot dome combustion and liner cooling air. The remaining 60% is used as catalyst air flow. Only the pilot stage is operated up to about 25% thrust. Above this level, pilot stage fuel flow is minimized and a majority of fuel flow is routed to the catalyst stage. At intermediate power levels, sector burning is utilized to control catalyst inlet fuel/air ratio. At higher power levels and during transients catalyst stage fuel flow is limited by catalyst maximum use temperature, and excess fuel is injected into the pilot stage. At the normal cruise condition, approximately 25% of the fuel is burned in the pilot stage.

Catalyst stage fuel flow is injected from orifices located in the central splitter vane of the inlet diffuser. A nominal flow velocity of 61 m/s is used in the premixing duct to provide adequate mixing length while meeting the 2 ms autoignition delay time requirement. Immediately upstream of the catalyst, the duct area is rapidly increased. The duct walls in this region are contoured to simulate the streamlines which would be observed in unconfined flow approaching the catalyst blockage.

Concept 4 (Figure 5) is a similar parallel staged design except that a cannular catalyst stage consisting of 30 cylindrical catalytic reactors is used. This catalyst stage has been relocated outboard of the pilot stage, and a reverse-flow configuration has been used to decrease combustor length. This cannular design provides advantages in fuel/air mixing duct velocity profile control and catalytic reactor access. Very uniform combustor exit temperature profiles are anticipated with this design because of improved mixing between the pilot and catalyst stages. Catalyst stage emissions and performance are also expected to be markedly improved during sector burning because individual reactors can be fueled, and the lean "fringe" area between fueled and unfueled annular sectors is avoided.

A problem common to both Concepts 3 and 4 is the inability to meet cruise $NO_x$ goals because a relatively large proportion of fuel (about 25%) must be burned in the pilot stage to avoid catalyst over temperature during cruise operation. In Concept 5(Figure 6), catalyst air flow at cruise condition is increased from 60 to about 80% by the use of variable geometry, thereby enabling approximately 95% of combustor fuel flow to be reacted in the catalyst. Within this concept, low power operations are conducted with the variable vanes closed. Under these conditions flow splits are similar to Concepts 3 and 4, but combustor pressure drop is increased to about 15%. Above the 25% thrust level, the variable geometry vanes are opened to increase catalyst flow to about 80% and reduce pressure drop to the 5% design level. As with Concept 2, the takeoff stage shown in this design was eliminated for the final evaluation.

Although $NO_x$ emissions reduction potential is improved with this design, the use of variable geometry results in a significant increase in mechanical complexity and control requirements. Of concern is decreased compressor stall margin due to increased pressure drop during idle operation, which leads to an increased risk of stall during transient operation.

Concept 6(Figure 7) is essentially two complete combustors in parallel. All operations within the landing/takeoff cycle are conducted with the outer combustor, which is a piloted premixing design based on the radial/axial configuration investigated in the NASA/GE Experimental Clean Combustor Program (Reference 4). When this combustor is in operation, the catalytic combustor vanes are closed, and only about 10% leakage flow passes through the catalyst. At cruise conditions, the variable geometry vanes are rotated to direct as much as 90% of combustor air flow to the catalytic combustor located in the inner annulus. Instead of sector burning in this design, catalyst inlet fuel/air ratio is controlle by opening the main stage control vanes to bypass air flow around the catalytic combustor.

This design approach takes maximum advantage of conventional combustor design technology since the outboard mounted combustor used for landing/takeoff maneuvers can be of conventional design. The required range of operation of the catalytic combustor is thus limited to cruise range conditions, which results in less severe operating constraints for the catalytic reactor and fuel/air carburetion system. On the other hand, this system does not take advantage of the catalytic combustor emissions reduction potential during landing/takeoff maneuvers. Transition from main combustion to catalytic combustor operation also presents a major control challenge, and overall system length, weight, and complexity are increased with this design.

Concept Evaluation

A conceptual design evaluation summary is presented in Table V, where the six conceptual designs are ranked with respect to predicted emission and developmental risk in several areas of combustor performance. The overall trend observed in the evaluation of these concepts is increased emissions reduction potential with increasing development risk. The parallel staged, non variable geometry concepts (BP and CRP) consistently rated highest in performance, but were lowest rated with respect to emissions. Therefore, the selection of the two most promising designs depended largely on the relative weighting of emissions and performance.

Predicted emissions for each of the combustor designs are presented in Table VI. As indicated in this figure, although cruise $NO_x$ emissions for Concepts 3 and 4 were 2 to 3 times as high as those of the other concepts, absolute levels were an order of magnitude lower than emissions obtained with current technology combustors. These two concepts were therefore, selected for further study.

## Preliminary Designs

Preliminary designs of the selected concepts are shown in Figure 8. In these designs, major emphasis was placed on reducing combustor length and increasing catalyst air flow. Features used to increase catalyst air flow include the reduction of film cooling in the pilot dome and combustor aft section. By incorporating these features, predicted cruise $NO_x$ levels are decreased to about 1.2 to 1.4 g/kg, compared to about 2 g/kg in the conceptual designs.

## Conclusions

Based on ALECC Phase I studies, catalytic combustion appears to be a promising means for obtaining ultra low $NO_x$ emissions at aircraft cruise operating conditions. Levels below 2 g/kg appear to be obtainable without the use of variable geometry. Circumferential fuel staging appears to be a viable means for controlling catalyst inlet fuel/air ratio. Circumferentially non-uniform exit temperature patterns resulting from circumferential staging are expected to be acceptable because of the relatively low peak exit temperatures, which are catalyst limited.

Major challenges in the application of catalytic combustion to practical aircraft combustors include the following:

- Development of fuel/air carburetion systems to meet mixing and autoignition criteria.
- Development of catalyst, support, and mounting systems to obtain good high cycle performance (durability, thermal shock resistence).
- Development of advanced liner cooling techniques to reduce cooling flow requirements.
- Development of precise fuel/air ratio sensing and control techniques.

- Determination of the effects of circumferential staging on catalyst performance.

These will be major areas of study in the ALECC Phase II and III experimental programs.

## REFERENCES


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3. Spadaccini, LJ; "Autoignition Characteristics of Hydrocarbon Fuels at Elevated Temperatures and Pressures", ASME 76-GT-3, March, 1976.

4. Bahr, DW; and Gleason, CC: "Experimental Clean Combustor Program, Phase I Final Report", NASA-CR-134737,June 1975.

## ALECC PROGRAM SCOPE

### OVERALL PROGRAM

- PHASE I - DESIGN STUDY
- PHASE II - SCREENING TESTS
- PHASE III - COMBUSTOR REFINEMENT

### PHASE I

- DESIGN STUDY (COMPLETED 11/20/78)
- DEFINE 6 CATALYTIC COMBUSTOR CONCEPTS
- ANALYZE AND EVALUATE CONCEPTS
- PERFORM PRELIMINARY DESIGN ON TWO MOST PROMISING CONCEPTS

TABLE I

## ALECC DESIGN REQUIREMENTS AND GOALS

- DESIGNS BASED ON NASA/GE ENERGY EFFICIENT ENGINE CYCLE AND ENVELOPE
- EMISSIONS:
  - o $NO_x \leq$ 1G/KG @ CRUISE
  - o MEET 1979 EPA EMISSIONS STANDARDS
- COMBUSTION EFFICIENCY
  - o $\geq$99.9% @ TAKEOFF
  - o $\geq$99.5% @ CRUISE
  - o $\geq$99% @ ALL OTHER
- PERFORMANCE COMPARABLE TO REFERENCE ENGINE
  - o PRESSURE DROP $\leq$5%
  - o PATTERN FACTOR $\leq$.35(TAKEOFF, CRUISE)
  - o RELIGHT
  - o LINER COOLING
- OPERATIONAL CHARACTERISTICS SUITABLE FOR USE ON REFERENCE ENGINE (WITH APPROPRIATE CONTROL MODIFICATIONS).

TABLE II

## COMPARISON OF CATALYST PERFORMANCE WITH ENGINE OPERATING REQUIREMENTS

| | ADVANCED CATALYST OPERATING RANGE | REFERENCE ENGINE CYCLE | | | |
|---|---|---|---|---|---|
| | | IDLE | APPROACH | CRUISE | TAKEOFF (MAX.) |
| INLET TEMP, K | 600-1100 | 485 | 633 | 677-782 | 864 |
| PRESSURE, MPA | — | 0.4 | 1.2 | 0.8-1.3 | 3.0 |
| EXIT TEMP, K | 1350-1811 | 940 | 1135 | 1289-1488 | 1693 |
| PRESSURE LOSS, % | 2-3 | 5.0 | 5.0 | 5.0 | 5.0 |
| COMBUSTION EFFICIENCY, % | 99.9 | 99.5 | 99 | 99 | 99.9 |
| $NO_X$ EMISSIONS | < 0.5G/KG | -- | -- | <1.0G/KG | -- |

TABLE III

## ALECC DESIGN CONSIDERATIONS

| DESIGN CONSIDERATION | POSSIBLE SOLUTION |
|---|---|
| IDLE INLET TEMPERATURE BELOW CATALYST IGNITION TEMPERATURE | – PREBURNER TO INCREASE CATALYST INLET TEMPERATURE – (SERIES STAGED)<br>– PILOT BURNER FOR IDLE OPERATION (PARALLEL STAGED) |
| MID RANGE COMBUSTOR EXIT TEMPERATURE BELOW TEMPERATURE REQUIRED FOR COMPLETE CONVERSION | – FUEL STAGING (SECTOR OR PARTIAL ANNULAR BURNING)<br>– AIRFLOW MODULATION (VARIABLE GEOMETRY) |
| MIXING/AUTOIGNITION | – AXIAL FUEL STAGING<br>– INCREASED FUEL MIXING TUBE VELOCITY<br>– MULTIPLE POINT INJECTION |

TABLE IV

# CATALYTIC COMBUSTOR ANALYSIS AND EVALUATION

| | CONCEPT RANKING<br>BEST ← → WORST<br>1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| EMISSIONS | VGS | BS | VGP | RAP | BP | CRP |
| OTHER CONSIDERATIONS | | | | | | |
| AEROTHERMAL | CRP | BP | VGS | BS | VGP | RAP |
| OPERATIONAL | CRP | BP | BS | VGS | VGP | RAP |
| FUEL/AIR CARBURETION | RAP | BP | CRP | VGP | BS | VGS |
| MECHANICAL | BP | CRP | BS | VGP | RAP | VGS |
| OVERALL | CRP | BP | VGP | BS | RAP | VGS |

BS - Basic Series Staged

VGS - Variable Geometry, Series Staged

BP - Basic Parallel Staged

CRP - Cannular Reverse-flow Parallel-staged

VGP - Variable Geometry Parallel-staged

RAP - Radial/Axial Parallel Staged

TABLE V