Technology for the Design of High Temperature Rise Combustors

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The results of analytical and experimental studies to determine the design technology needs of high temperature rise (ΔT) combustors and to define candidate design concepts for meeting these needs are reviewed. These studies show that several unique design considerations and constraints apply, because a high proportion of the available airflow must be allocated to the combustion process at the high ΔT operating conditions. This airflow allocation is necessary to obtain efficient combustion and acceptable smoke emission levels at the high ΔT conditions. Important technology needs include design features to provide stable operation over very wide ΔT ranges and design features to minimize liner-cooling airflow requirements. Candidate design concept features for providing these needed high ΔT combustor capabilities are described. Included are advanced design concepts to provide combustion process staging capabilities, as well as advanced liner-cooling and structural design concepts. The current development status of these various advanced design concepts is also assessed.

Introduction

TO improve engine thermodynamic performance and engine thrust-to-weight ratio, many future aircraft turbine engines are expected to operate with higher turbine inlet temperatures than those typical of current technology engines. The attainment of these increased turbine inlet temperatures requires combustors with higher temperature rise (ΔT) capabilities than those of current technology combustors. Thus, advanced combustors with acceptable performance, operability, and life capabilities, while operating with significantly higher fuel-air ratios, are needed. Because the overall combustor fuel-air ratios at starting and low power conditions must be essentially the same as those of current technology combustors to satisfy engine operability needs, these advanced combustors must be capable of operating satisfactorily over significantly wider fuel-air ratio ranges.

During the past several years, analytical and experimental investigations to evolve technology for the design of high ΔT combustors have been conducted by the General Electric Aircraft Engine Business Group. The objectives of these investigations were to determine the unique design technology needs of high ΔT combustors, and to identify candidate design concepts for meeting these needs. The important findings of these various effects are reviewed herein.

Technology Needs

Throughout this paper, combustor ΔT is defined as the average temperature (T_4) of the gas entering the high-pressure turbine vanes minus the compressor discharge air temperature (T_3). The combustor ΔT requirements of modern operational engines nominally extend up to approximately 1500°F in the case of turbofan engines used in commerical aircraft, and to approximately 1700°F in the case of turbofan engines used in military engines. These nominal ΔT levels respectively correspond to overall combustor fuel-air ratio (ratio of fuel mass flow rate to air mass flow rate) values on the order of 0.025 and 0.030, see Fig. 1. The combustor ΔT requirements of some future engines are forecasted to extend up to 2500°F or higher. For $\Delta T = 2500$°F, the corresponding combustor fuel-air ratio is about 0.047, Fig. 1. Thus, very substantial increases in combustor fuel-air ratio must be accommodated in high ΔT combustors.

Satisfactory combustor performance at low ΔT operating conditions is also an important requisite. In particular, stable operation down to combustor fuel-air ratios as low as 0.005 is a key requirement of many modern operational engines to prevent flameout during a throttle chop from high engine power settings to idle power. Acceptable starting and altitude relight capabilities are also important requirements. The latter required capabilities and the lean blowout requirement are closely interrelated. With a lean blowout fuel-air ratio of 0.005 or less, the associated starting and altitude relight capabilities of a given combustor configuration are usually acceptable.

Because the low power operability requirements of future engines with high ΔT combustors are expected to be essentially the same as those of current technology engines, a lean blowout fuel-air ratio of about 0.005 is also a needed capability of high ΔT combustors. As a result, much wider fuel-air ratio ranges must be satisfactorily accommodated in high ΔT combustors than in current technology combustors, as is illustrated in Fig. 1. The combustor performance, operability, and durability impacts of these much wider fuel-air ratio ranges are very substantial.

One consequence of high ΔT operation is its impact on primary zone stoichiometry. An illustration of the effect of high ΔT operation on the average primary zone fuel-air equivalence ratio (actual fuel-air ratio divided by stoichiometric fuel-air ratio) of a current technology combustor is shown in Fig. 2. The combustor used in this illustration is the F101 engine combustor. The F101 is a modern operational turbofan engine, and its combustor is a compact and short-length configuration with excellent performance, operability, and life capabilities. As shown in Fig. 2, visible smoke emissions were prevented by designing the combustor with an adequately lean primary zone at its highest overall fuel-air ratio.

However, if operated in a high ΔT mode with an overall fuel-air ratio of about 0.047 rather than with its design value of about 0.030, this F101 combustor would have visible smoke emissions because of the much higher average primary zone equivalence ratio. Based on an F101 combustor correlation of smoke number with average primary zone

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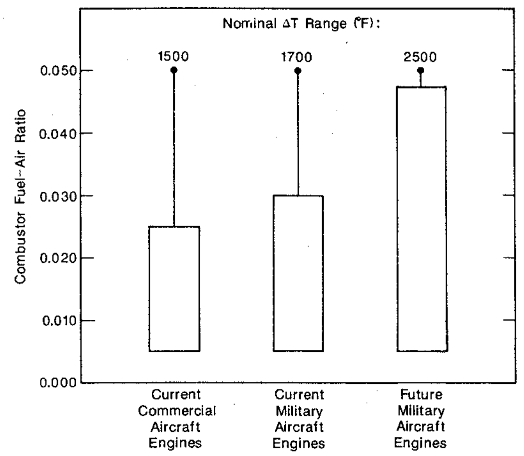

Fig. 1 Typical combustor fuel-air ratio operating range requirements of turbofan engines.

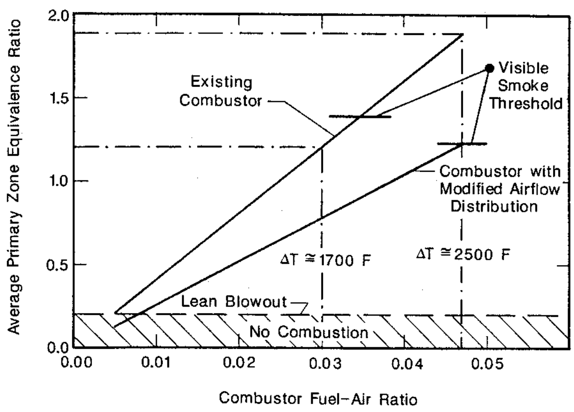

Fig. 2 Primary zone equivalence ratio—combustor fuel-air relationships of F101 combustors.

equivalence ratio and with fuel flow rate per injector, a fuel-air ratio increase from 0.030 to 0.047 would increase the smoke number (with JP-5/JP-8 fuels) at the combustor exit from 14 to 39. The latter smoke number is well into the range of smoke emission visibility.

Because of the critical importance of operating with invisible smoke emissions in both commercial and military aircraft applications, these F101 combustor analyses demonstrate that provisions to supply significantly increased fractions of the combustor airflow to the primary zone are an important need of high ΔT combustors. It is possible to incorporate such provisions into the existing F101 combustor by redistributing the combustor airflow. Based on the F101 combustor smoke number correlation, an estimated increase in the primary airflow allocation from the existing value of 36.4% to a value of 55.9% of the total combustor airflow would be needed. This airflow redistribution would involve a large reduction in the existing liner dilution airflow allocation and an accompanying increase in the primary zone allocation. The resulting average primary zone equivalence ratio/combustor fuel-air relationships of the modified combustor configuration are shown in Fig. 2.

In addition to reducing the average primary zone equivalence ratio at the high ΔT conditions, this design change would, of course, reduce the average primary zone equivalence ratios at the low combustor fuel-air ratio operating conditions, as indicated in Fig. 2. The combination of this increased primary zone leanness and the associated higher primary zone gas velocities would be expected to

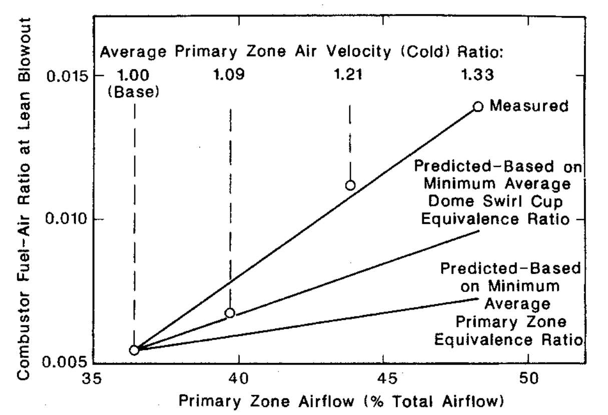

Fig. 3 Effect of primary zone airflow allocation on lean blowout characteristics of F101-type combustor, with JP-4 fuel.

Table 1 Comparison of combustor airflow allocations

	Combustor configuration	
	Existing F101	Modified F101[a]
Design ΔT maximum, °F	1700	2500
Airflow allocation (% total combustor airflow)		
Primary zone	36.4	55.9
Dilution (via aft liner dilution ports)	28.6	0.6
Liner cooling	35.0	43.5
Total	100	100

[a]Primary zone airflow increased to maintain essentially the same smoke level as in existing engine applications.

result in large increases in the combustor lean blowout fuel-air ratios.

Some test results, which illustrate the impacts of higher primary zone airflow allocations on lean blowout characteristics, are presented in Fig. 3. These results were obtained in tests of an F101-type combustor, in which the primary zone airflow allocation was progressively increased by increases in the dome swirl cup flow area and equivalent decreases in the liner-cooling flow area. Included in Fig. 3 are the predicted increases in lean blowout fuel-air ratio that would result if it is assumed that a minimum average primary zone equivalence ratio is needed to prevent blowout.

The predicted values, if it is instead assumed that a minimum average dome swirl cup equivalence ratio is needed to prevent blowout, are also shown in Fig. 3. The difference in the two prediction lines is due to the fact that the primary zone airflow is composed of elements in addition to that of the dome swirl cups. In the F101-type combustor used for these tests, the primary zone airflow increases were entirely obtained via increases in the flow area of the dome swirl cups. As a result, the percentage increases in dome swirl cup airflow were greater than those in the total primary zone airflow. Therefore, the predicted increases in lean blowout fuel-air ratio, associated with an assumption of a minimum average dome swirl cup equivalence ratio, are somewhat greater.

In any case, the measured increases in lean blowout fuel-air ratio were considerably higher than the predicted values shown in Fig. 3. The differences between the values predicted from stoichiometry considerations and the measured values are indicative of the effects of the accompanying increases in average primary zone velocity.

Thus, a key design concern of high ΔT combustors is obtaining both low smoke levels at high power conditions and acceptable lean blowout fuel-air ratios at low power conditions. To obtain these capabilities, provisions for providing suitably lean primary zone equivalence ratios at high ΔT conditions, without adversely impacting low ΔT operation, are required. Based on the preceding assessments, it is concluded that such provisions must involve concepts for modulating primary zone stoichiometry.

Assuming that satisfactory means of modulating primary zone stoichiometry can be evolved, another key technology need of high ΔT combustors is minimizing the required quantities of liner-cooling airflow. At the high ΔT operating conditions, a larger percentage of the combustor airflow must be allocated to the primary zone for the above-discussed reasons. Consequently, if the required liner cooling airflow quantity is not minimized, very little dilution airflow is available for the necessary control and tailoring of the exit gas temperature distributions.

An illustration of the magnitude of this liner-cooling airflow concern is presented in Table 1. In this tabulation, the combustor airflow allocation of the existing F101 combustor, which is designed for a maximum ΔT of about 1700°F, is compared with that of the above-described modified combustor, with its intended maximum ΔT of about 2500°F. In addition to its significantly increased primary zone airflow allocation, an increased liner-cooling airflow allocation would also be needed because of the higher exit gas temperatures and the resulting higher heat loads to the downstream liner sections. As is shown, the dilution airflow allocation would be virtually eliminated. As such, satisfactory control of the exit gas temperature distributions would not be possible.

To resolve this concern, reductions in the liner-cooling airflow requirements are essential. In view of the higher overall liner heat loads associated with high ΔT operation, meeting this need is an especially formidable challenge.

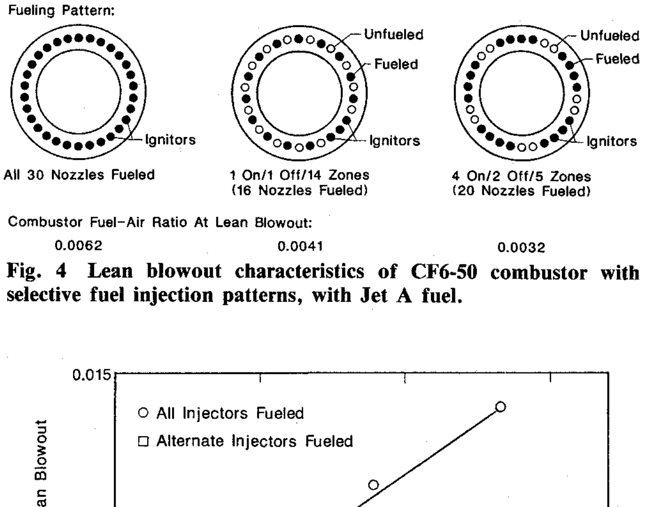

Fig. 4 Lean blowout characteristics of CF6-50 combustor with selective fuel injection patterns, with Jet A fuel.

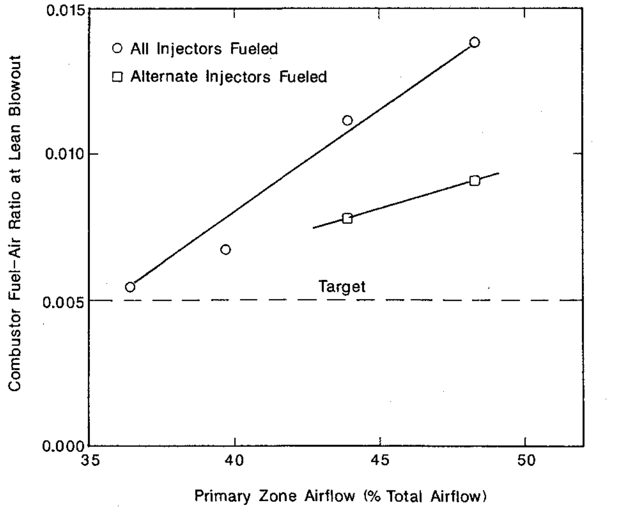

Fig. 5 Effect of selective fuel injection patterns on lean blowout characteristics of F101-type combustor, with JP-4 fuel.

Clearly, more effective liner-cooling methods are an important technology need of high ΔT combustors.

Accordingly, the key technology needs of high ΔT combustors are provisions for primary zone stoichiometry modulation and for minimizing liner-cooling airflow demands, as summarized in Table 2. Included in Table 2 are various general design concepts for meeting these needs. The collective results of several analytical and experimental investigations to identify, define, develop, and evaluate such design concepts are summarized in the following discussions.

Primary Zone Stoichiometry Modulation Concepts

Several approaches can be considered for modulating average primary zone equivalence ratios to provide the values needed for acceptable performance capabilities at both high and low ΔT operating conditions, even though the overall combustor fuel-air ratios vary over a wide range. These approaches involve either fuel- or air-staging techniques, or combinations of both.

Candidate fuel-staging techniques include the use of selective fuel injection, which provides local fuel-air ratio enrichment at low ΔT conditions, and the use of separate combustion zones within the combustor. Air-staging techniques involve the use of variable geometry of various kinds within the combustor. Versions of each of these candidate techniques were defined and evaluated. The following are the key results of these investigations.

Fuel-Staging Concepts

Selective Fuel Injection

The use of selective fuel injection provides a relatively simple means of modulating primary zone stoichiometry. With this technique, fuel is valved to selected combinations of fuel injectors at lightoff, altitude relight, and idle operating conditions, rather than to the full complement. At all engine power settings above idle, the full complement of fuel nozzles is operational. The intent of this modulation technique is to provide increased primary zone fuel-air ratios within portions of the combustor annulus at the low ΔT conditions.

The use of selective fuel injection has been investigated extensively for use in conventional ΔT combustors as a means of reducing hydrocarbon and carbon monoxide emission levels.[1] The same techniques have also been found to provide reduced lean blowout fuel-air ratios. An illustration of the effects of selective fuel injection on lean blowout characteristics is presented in Fig. 4. These test results were obtained with a CF6-50 engine combustor that is equipped with 30 pressure-atomizing fuel nozzles. As is shown, significant improvements in lean blowout capabilities were realized with the selective fuel injection patterns.

An evaluation was conducted of a selective fuel pattern—alternate injectors fueled—in the above-described F101-type combustor, in which the primary zone airflow allocation was progressively increased. The results obtained

Table 2 Technology needs of high ΔT combustors

Concepts for primary zone stoichiometry modulation
Fuel staging via localized fuel-air enrichment and/or dual combustion zones
Air staging via variable-geometry features to adjust combustor airflow distribution
Concepts for minimizing liner-cooling airflow
Reduced combustor length
Thermal barrier coatings
Enhanced cooling effectiveness
Advanced structures
Higher temperature liner materials

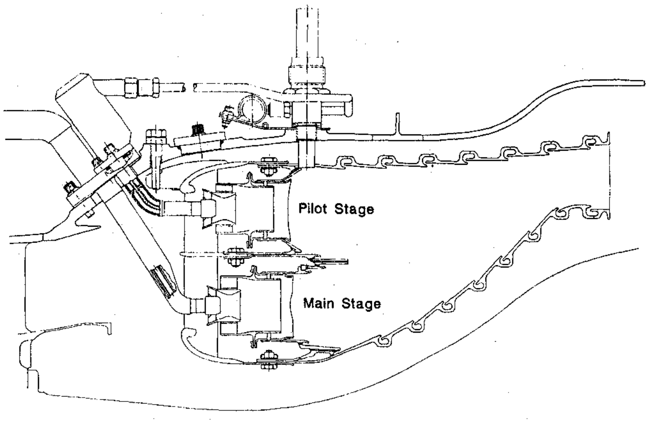

Fig. 6 Cross-sectional drawing of ECCP/CF6-50 dual annular combustor.

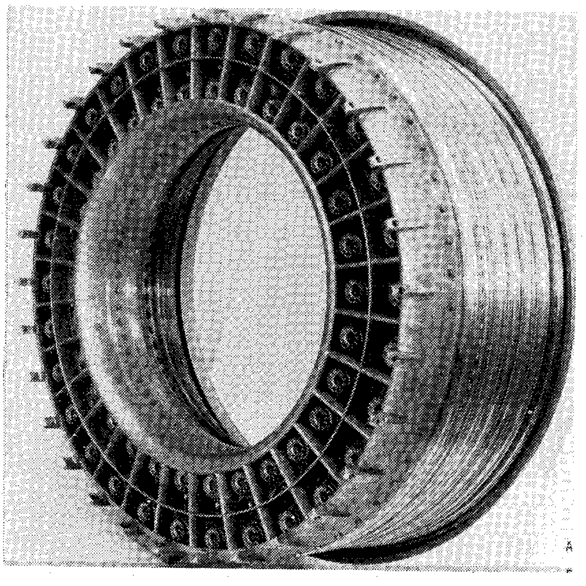

Fig. 7 ECCP/CF6-50 dual annular combustor.

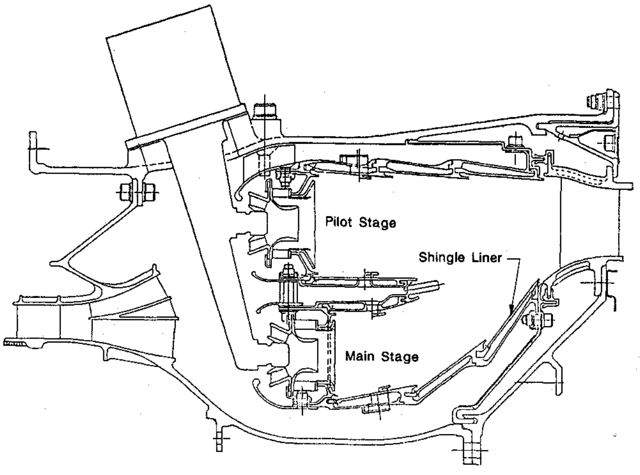

Fig. 8 Cross-sectional drawing of E^3 dual annular combustor.

Fig. 9 E^3 dual annular combustor.

in this evaluation are presented in Fig. 5. As expected, significant improvements were obtained. However, with the primary zone airflow allocations needed for satisfactory high ΔT operation, the resulting lean blowout fuel-air ratios were still relatively high and above the target value. These lean blowout fuel-air ratios were still high because of the adverse impacts of the high average primary zone velocities associated with the high primary zone airflow allocations.

Within the available combustor envelope of a current technology engine, it is not usually possible to obtain an acceptably low average primary zone velocity along with a higher primary zone airflow. In a new high ΔT combustor design for a new engine application, it is possible to provide both the needed high primary zone airflows and acceptably low average primary zone velocities. To do so, however, a large primary zone flow area is needed. This need results in a relatively large combustor dome (primary zone) radial height. In turn, the large radial dome height generally results in a relatively long combustor burning length, because of the direct dependence of burning length on dome height.

This indicated need for larger and longer combustors, even with selective fuel injection to improve lean blowout capability, is very unattractive. Compact combustors with short burning lengths are important requisites of advanced engines to reduce weight and to minimize combustor liner-cooling airflow requirements. It was concluded, therefore, that conventional combustor designs, even with selective fuel injection, are generally unsuitable in high ΔT applications.

Dual Annular Combustors

The development of combustors with combustion process staging via separate combustion zones has been extensively pursued as a means of obtaining reduced pollutant emission levels, especially reduced nitrogen oxides (NO_x) levels.[2,3] In these development efforts, advanced combustor concepts with separately fueled combustion zones were evolved. Configurations with zones in parallel as well as with zones in series were investigated. In addition to offering the potential for reduced pollutant emission levels, these advanced combustor concepts are also candidates for high ΔT applications.

One design concept of this kind is the dual annular combustor.[4] This concept features the use of two primary combustion zones in parallel. Both annuli, or zones, are individually fueled. In this parallel-staged concept, one of the annuli—usually the outer annulus—is designed to operate with lower airflows than the other annulus and to serve as the pilot stage. The other annulus is designed with a high airflow and serves as the main stage. Only the pilot stage is fueled at starting, altitude relight, and idle conditions. In this manner, adequately rich fuel-air ratios and low air velocities are obtained in this annulus at the low ΔT conditions. At operating conditions above idle, both annuli are fueled. The fuel flow splits to the two annuli can be adjusted to provide lean fuel-air ratios in both annuli at conventional ΔT conditions and near-stoichiometric fuel-air ratios at high ΔT conditions. Thus, at high ΔT conditions, efficient combustion with low smoke levels is obtainable.

A version of this design concept has been designed and developed for use in the CF6-50 engine as a part of the NASA/General Electric Experimental Clean Combustor Program (ECCP).[5,6] A cross-sectional drawing and a photograph of this dual annular combustor are presented, respectively, in Figs. 6 and 7. Subsequently, another version was designed and developed for use in the NASA/General Electric Energy Efficient Engine (E^3).[7,8] A cross-sectional drawing and a photograph of the latter dual annular combustor are presented, respectively, in Figs. 8 and 9. Both of these dual annular combustors were evaluated and demonstrated in engine tests.

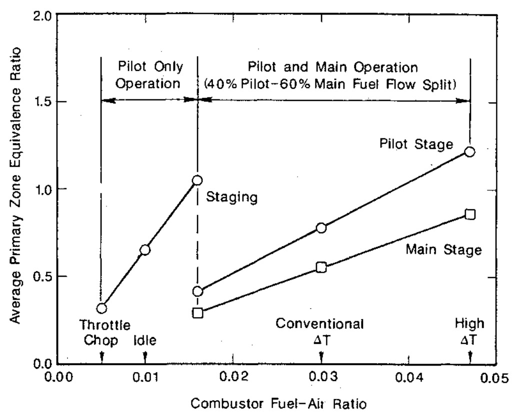

Fig. 10 Primary zone equivalence ratio—combustor fuel-air ratio relationships of ECCP/CF6-50 dual annular combustor.

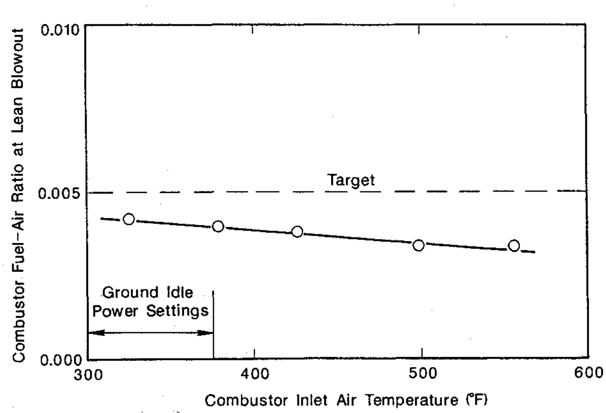

Fig. 11 Lean blowout characteristics of ECCP/CF6-50 dual annular combustor, with Jet A fuel.

These two dual annular combustors were specifically designed for operation at conventional ΔT levels, but with low NO_x levels. As such, they were designed to operate with below-stoichiometric primary zones at their highest design ΔT levels. At high ΔT conditions, therefore, these same designs would operate with near-stoichiometric primary zones. As an illustration, the pilot and main stage equivalence ratios of the ECCP/CF6-50 configuration are shown as a function of overall combustor fuel-air ratio in Fig. 10. As is shown, the average primary zone equivalence ratios at fuel-air ratios corresponding to high ΔT operation are near unity.

The measured lean blowout characteristics of the ECCP/CF6-50 configuration are shown in Fig. 11. Satisfactory lean blowout capabilities with pilot stage only operation were obtained. Because the combustor operating conditions and requirements at these low ΔT conditions would be essentially the same if the combustor were to be used in a high ΔT application, these results indicate that satisfactory lean blowout capabilities would also be obtained in a high ΔT application.

These dual annular combustors were not evaluated at high ΔT conditions. However, based on the favorable primary zone equivalence ratios obtainable with such combustor designs at high ΔT conditions (see Fig. 10), efficient combustion with low smoke levels would be expected. Another advantage of this design concept is its short burning length. Because of its dual annular feature, a satisfactory length-to-dome height relationship in each dome (annulus) is obtained within a short overall length. This short-length feature is attractive from the standpoints of minimizing engine weight and liner-cooling airflow requirements.

Based on these analyses, it is concluded that dual annular combustors of this kind offer an attractive means of pro-

Table 3 Low ΔT performance characteristics of BSFCTP/CF6-80 combustor with Jet A fuel

	Measured	Target
Lean blowout fuel-air ratio	0.0045	0.0050 (max)
Combustion efficiency at idle power, %	97.6	99.0 (min)
Pressure loss at idle power, %	5.3	—

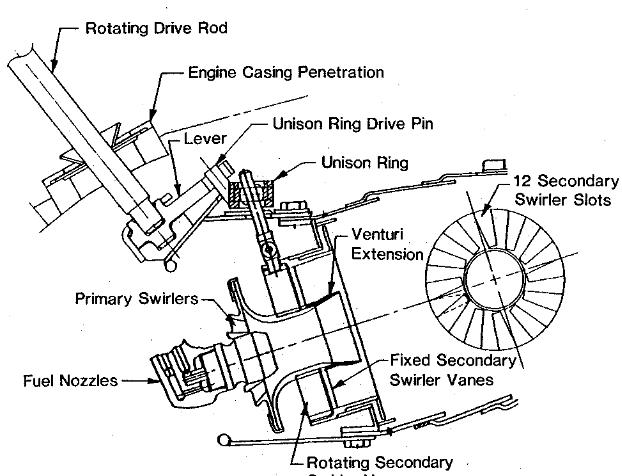

Fig. 12 Cross-sectional drawing of BSFCTP/CF6-80 variable-geometry combustor forward end.

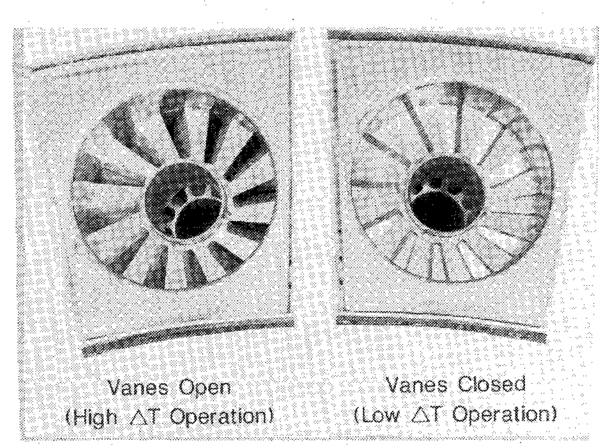

Fig. 13 BSFCTP/CF6-80 variable-geometry combustor swirl cup vane positions.

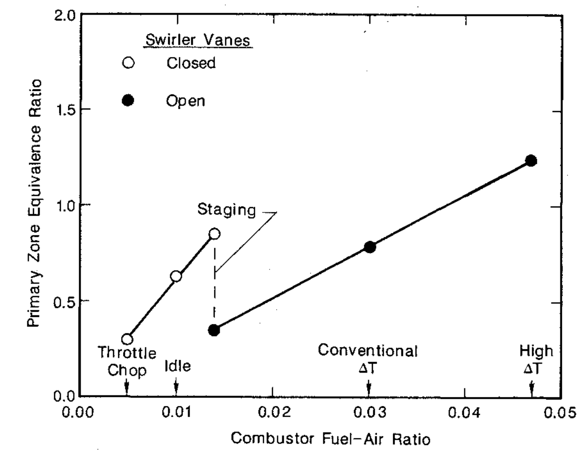

Fig. 14 Primary zone equivalence ratio—combustor fuel-air ratio relationships of BSFCTP/CF6-80 variable-geometry combustor.

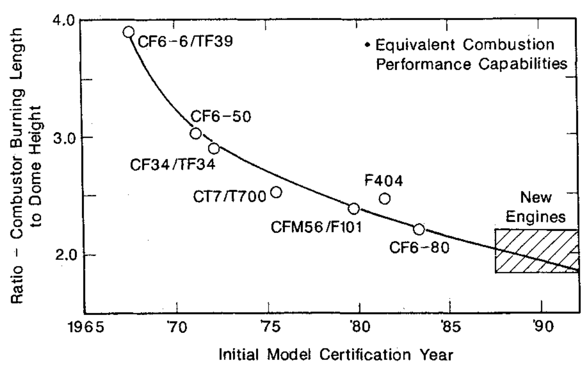

Fig. 15 Progress trends in development of compact and short-length combustors.

viding the primary zone stoichiometry modulation needed in high ΔT combustors.

Air-Staging Concepts

Several variable-geometry approaches to adjust and regulate the airflow distributions of combustors are possible. These approaches include variable-area features in the combustor inlet cowl, dome swirl cups, and liner dilution ports, as well as combinations thereof. As a means of providing the needed low primary zone airflows at low ΔT conditions and high primary zone airflows at high ΔT conditions, the use of variable-geometry features in the swirl cups is especially attractive from a combustion performance standpoint. This design approach provides direct regulation of the most influential primary zone airflow quantity. To some extent, the latter type of approach generally involves more mechanical complexity than other variable-geometry approaches. However, almost all variable-geometry approaches evolved to date are generally complex and unattractive from a mechanical-design standpoint.

An advanced, short-length combustor with variable-geometry features in its swirl cups was designed and developed as a part of the NASA/General Electric Broad-Specification Fuels Combustion Technology Program (BSFCTP) for use in the CF6-80 engine.[9] A cross-sectional drawing of the forward end of this combustor is presented in Fig. 12. In this design, the swirl cup airflow is varied by rotating the secondary swirler vanes relative to a fixed register plate mounted at the rotating vane package exit, see Fig. 13. The variable vanes are mounted on the primary swirler venturi, and are driven by a rotating unison ring which engages a drive pin at each cup location. The unison ring is driven by a drive rod and lever which penetrate the

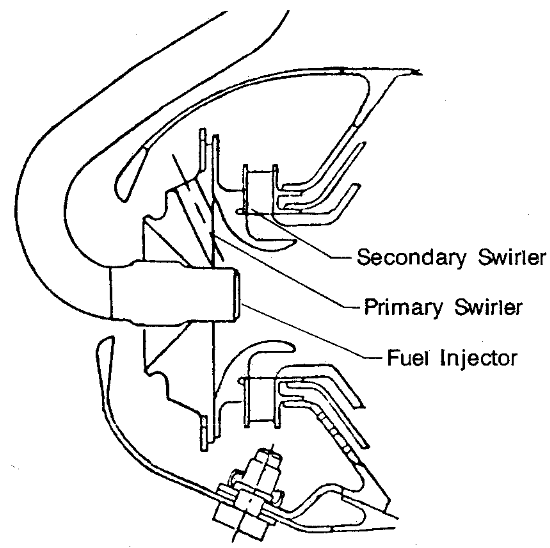

Fig. 16 Cross-sectional drawing of F101 combustor dome swirl cup configuration.

engine casing. At low ΔT conditions, the swirlers are closed to provide acceptably low primary zone velocities and adequately rich fuel-air ratios. At high ΔT conditions, the swirlers are opened to maintain lean or near-stoichiometric fuel-air ratios in the primary zone. With this concept, higher combustor pressure drops result at the low ΔT conditions when the vanes are closed.

This BSFCTP CF6-80 variable-geometry combustor was not specifically designed for operation at high ΔT levels. It was, however, designed to operate with below-stoichiometric average primary zone fuel-air ratios at conventional ΔT levels. As such, this same basic design would operate with a near-stoichiometric average primary zone equivalence ratio at high ΔT conditions, as is illustrated in Fig. 14.

With this design, acceptable lean blowout characteristics were obtained, as is indicated in Table 3. Essentially the same results would be expected if this combustor were to be used in a high ΔT application. Also, based on the favorable primary zone equivalence ratios obtainable with this combustor design concept at high ΔT conditions (see Fig. 14), efficient combustion with low smoke levels would be expected. As in any design that operates with low primary zone airflows at low ΔT conditions, this variable-geometry configuration can be designed with a small dome height and, as a result, a short burning length.

Based on these analyses, it is concluded that variable-geometry combustors of this kind offer another attractive means of providing the primary zone stoichiometry modulation needed in high ΔT combustors.

Concepts for Minimizing Liner-Cooling Airflow

As indicated in Table 2, several approaches can be considered for minimizing liner-cooling airflow requirements. One basic approach is to minimize the liner surface area by reducing combustor burning length. To a first approximation, the required quantity of cooling airflow in a given combustor is directly proportional to its burning length.

Within recent years, substantial gains have been made in reducing burning length (Fig. 15). These gains were realized without losses in combustion efficiency, deterioration of exit gas temperature distribution quality, or losses in other aspects of combustion performance. The positive impacts on combustor durability and life have been very significant. These length reductions were achieved primarily by improvements in the fuel injection and fuel-air mixing provisions. In the case of the short-length combustors included in Fig. 15, the length reductions were specifically obtained as a

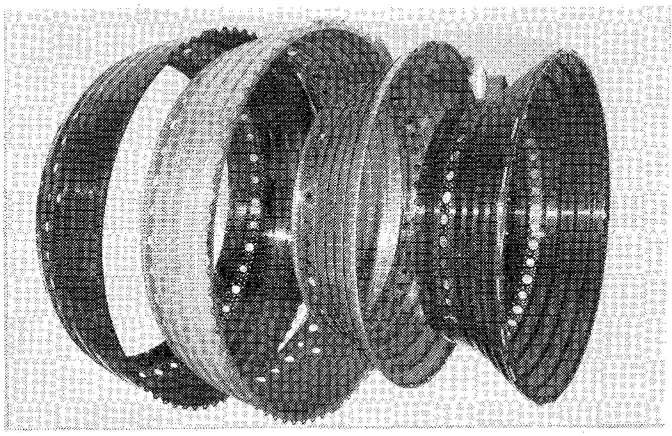

Fig. 17 Impingement plus film-cooled liner configuration.

Table 4 Comparison of combustor airflow allocations with advanced liner-cooling features

Combustor configuration: modified F101 with increased primary zone airflow
Design ΔT maximum: 2500°F

Airflow allocation (% total combustor airflow)	Baseline	Liner-cooling features: Thermal barrier coating	Liner-cooling features: Impingement plus film cooling
Primary zone	55.9	55.9	55.9
Dilution (via aft liner dilution ports)	0.6	4.4	17.6
Liner cooling	43.5	39.7	26.5
Total	100	100	100

result of advanced dome swirl cup configurations. The significant design features of these advanced configurations are high airflow levels and counterrotating swirlers to provide good fuel atomization and rapid fuel-air mixing at all combustor operating conditions. A configuration of this kind—the F101 combustor dome swirl cup—is illustrated in Fig. 16.

The use of thermal barrier coatings on the liners has also been found to provide a means of reducing liner-cooling airflow requirements. Within recent years, layered coatings of magnesium or yttria zirconate have been evolved and used in operational engines. The durability characteristics of these coatings have proven to be excellent. The estimated cooling airflow reduction obtainable with a thermal barrier coating in the high ΔT F101-type combustor described previously (see Table 1) is shown in Table 4. This estimate is based on the assumption of constant liner metal temperatures, with and without the coating. As is shown, the use of a thermal barrier coating is predicted to provide a modest reduction in the required liner-cooling airflow.

Larger cooling airflow reductions can be obtained via techniques for supplementing the film-cooling provisions used in current technology combustors. The use of both convective and impingement cooling techniques, in conjunction with film cooling, has been investigated. In particular, these investigations have shown that the combined use of impingement plus film cooling can provide much more effective cooling with a given quantity of cooling airflow than is obtainable with film cooling only.[10] An impingement plus film-cooled liner, which was developed for use with a F101-type combustor, is shown in Fig. 17. As is shown, both the inner and outer liner assemblies are comprised of two shells—a shell with many small holes to direct jets of cooling air onto the hot shell and a second shell with film-cooling provisions. The cooling airflow reduction obtainable with this liner in the high ΔT F101-type combustor is shown in Table 4. This estimate is based on the assumption of constant liner metal temperatures, with and without the use of this advanced cooling technique. As is shown, the use of this technique is predicted to provide a significant cooling airflow reduction and, as a result, a large increase in dilution airflow.

To obtain good durability and life characteristics along with minimal cooling airflow requirements, an advanced structural design concept was specifically developed for use in impingement plus film-cooled liners. This concept involves the use of segmented panels, or shingles, in the hot shells (see Fig. 18). In this liner design concept, shingles are used as heat shields to protect the 360-deg load-carrying support structure. The cooling airflow is first used to provide impingement cooling of the shingles, and is then used to provide film cooling. The individual shingles are mounted on the support structure. As such, the hot shingled panels are mechanically decoupled from the relatively cool support

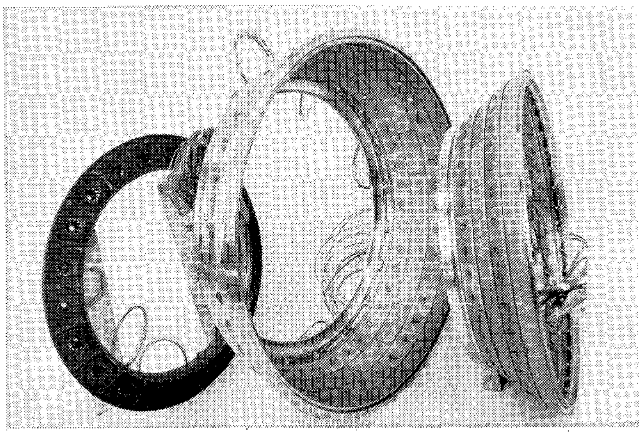

Fig. 18 Shingle liner configuration.

structure. Consequently, reduced thermal stress levels within the liner structure and significantly improved liner cyclic life characteristics are obtained. The liner shown in Fig. 18 was successfully demonstrated at high ΔT operating conditions in an extensive series of performance and durability tests. To obtain reduced liner-cooling airflow, together with long life, this liner design concept was also used in the E^3 combustor, as shown in Fig. 8.

Another important means of reducing the required quantity of cooling airflow in a given combustor design is to allow the liners to operate at higher temperatures. To obtain acceptable liner life and durability, this approach, of course, requires the use of higher temperature materials than those generally used in current combustors. Candidate advanced materials for applications of this kind include advanced alloys, carbon/carbon composites, and ceramic composites.

Accordingly, significant progress has been made in the development of technology to meet the liner-cooling requirements of high ΔT combustors. The combined use of short burning lengths, thermal barrier coatings, augmentation of the film cooling with other cooling mechanisms, and advanced structural concepts appears especially attractive as a means of meeting this high ΔT combustor design need.

Concluding Remarks

In summary, considerable technology is available for the design and development of high ΔT combustors, especially with respect to long-life liner designs with minimal cooling airflow requirements.

At the expense of some added fuel injection and primary zone complexity, the use of advanced combustors with separately fueled combustion zones offers a workable means of obtaining the needed primary zone fuel-air ratio modulation. In particular, the use of dual annular concepts for this purpose offers considerable promise.

As an alternative to fuel injection staging, the use of combustion airflow staging via variable-geometry features is also advantageous from a combustion performance standpoint. Near-optimum control of primary zone stoichiometry is potentially obtainable with staging methods of this type. However, the mechanical implementation of such staging methods is generally complex and difficult. A key technology need of high ΔT combustors is, therefore, technology for the design of variable-geometry features, which are relatively simple, reliable, and lightweight. Preferably, systems are needed that can be positioned without the need for mechanical linkages to external actuation and control equipment. While some progress has been made in the development of variable-geometry features, much additional development is needed before the full potential of this attractive design approach can be realized in future high ΔT combustors.

References

[1]Bahr, D.W., "HC and CO Emission Abatement Via Selective Fuel Injection," ASME Paper 82-GT-178, April 1982.

[2]"Aircraft Engine Emissions," NASA CP 2021, 1977.

[3]Bahr, D.W., "Gas Turbine Engine Emission Abatement—Status and Needed Advancements," *Project Squid Workshop on Gas Turbine Design Problems,* Hemisphere, 1980, pp. 205-223.

[4]Bahr, D.W. and Gleason, C.C., "Experimental Clean Combustor Program—Phase I Final Report," NASA CR-134737, June 1975.

[5]Gleason, C.C., Rogers, D.W., and Bahr, D.W., "Experimental Clean Combustor Program—Phase II Final Report," NASA CR-134971, Aug. 1976.

[6]Gleason, C.C. and Bahr, D.W., "Experimental Clean Combustor Program—Phase III Final Report," NASA CR-135384, May 1979.

[7]Sokolowski, D.E. and Rohde, J.E., "The E^3 Combustors: Status and Challenges," NASA TM 82684, July 1981.

[8]Bucy, R.W., "Progress in the Development of Energy Efficient Engine Components," ASME Paper 82-GT-275, April 1982.

[9]Dodds, W.J., Ekstedt, E.E., Bahr, D.W., and Fear, J.S., "NASA/General Electric Broad-Specification Fuels Combustion Technology Program: Phase I," *Journal of Energy,* Vol. 7, Nov.-Dec. 1983.

[10]Bahr, D.W., "Design Technology for Future Aircraft Turbine Engine Combustors," AIAA Paper 79-1197, June 1979.