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NASA BROAD-SPECIFICATION FUELS COMBUSTION TECHNOLOGY PROGRAM - STATUS AND DESCRIPTION

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ABSTRACT

The use of "broad-specification" fuels in aircraft gas turbine engines can be a significant factor in offsetting anticipated shortages of current-specification jet fuel in the latter part of the century. The changes in fuel properties accompanying the use of broad-specification fuels will tend to cause numerous emissions, performance, and durability problems in currently-designed combustion systems. The NASA Broad-Specification Fuels Combustion Technology Program is a contracted effort to evolve and demonstrate the technology required to utilize broad-specification fuels in current and next generation commercial Conventional Takeoff and Landing (CTOL) aircraft engines, and to verify this technology in full-scale engine tests in 1983. The program consists of three phases: Combustor Concept Screening, Combustor Optimization Testing, and Engine Verification Testing. Phase I contracts have been awarded to the General Electric Company and the Pratt & Whitney Aircraft Group of the United Technologies Corporation to evolve and screen combustion system designs for the CF6-80 engine and the JT9D-7 engine, respectively, in high-pressure sector test rigs.

INTRODUCTION

Since the advent of the jet engine, there has been an abundance of high-quality middle distillates from petroleum available to be used as jet fuel. The availability of high-quality fuels from straight distillation is expected to diminish toward the end of this century because of diminishing supplies and the resulting competition for the available middle distillates. Higher-boiling-point fractions can be cracked and hydrogenated to force them to meet present specifications, or lower-quality feedstocks, such as crude oils derived from oil shale or coal, can be refined to present specifications; however, these would be expensive and high-energy-consuming processes. The alternative to altering the fuel is to modify the jet engine, in particular the combustion system, to accept fuels with less stringent specifications. This course would involve large initial expenditures for combustion system development and for modification of in-use engines designed for the use of higher-quality fuel, but has the benefit of reduced fuel-processing costs over the lifetime of the engine. Whether the latter course can be shown to be the economically-sound choice depends on the obtaining of the solutions to a number of problems incurred in the use of broad-specification fuels:

1. Aromatics content will be higher than in presently-used fuels. This will tend to cause:
    a. Increased engine visible smoke output.
    b. Increased carbon deposition on fuel nozzles and combustor liners.
    c. Increased flame luminosity, resulting in increased radiative heat transfer to combustor liners, and shorter liner life.
2. Fuel volatility will be lower than in presently-used fuels, causing:
    a. More difficult cold start and altitude relight.
    b. Greater difficulty in achieving satisfactory emissions levels at low-power conditions.
3. Fuel viscosity will be higher than in presently-used fuels, making atomization more difficult, and causing the same problems as are caused by decreased volatility.
4. Thermal stability may be poorer than in presently-used fuels, causing:

a. Fuel system deposits.
b. Fuel injector plugging.

Measures taken to solve these problems can cause further problems to surface. For example, the increased combustor liner temperatures resulting from higher flame luminosity can be offset by the use of more liner-cooling air; however, this would result in less air being available for dilution purposes, to tailor exit-temperature profiles. Since modern high-performance engines often already have a minimum amount of dilution air available, increasing the liner-cooling air would put an additional burden on engine hot parts. Also, additional liner-cooling air might have a quenching effect on combustion reactions, increasing emissions. Thus, advanced liner-cooling technology will be investigated as part of this program.

Ultimately, the choice between the extensive processing of broad-specification fuels to meet present jet fuel specifications and the use of these fuels with limited processing, but with possibly significant combustion system modifications, will be based on both relative costs and the energy-intensiveness of the refining processes. It is entirely possible that the optimum choice will be a compromise, with some fuel treatment and some combustion system modifications. The technology to be acquired in this program will serve to define the complexities of the approach in which combustion system modifications are made as required in order to minimize fuel processing.

PROGRAM DESCRIPTION

Program Plan

The program is being conducted in three separately-funded phases:

Phase I: Combustor Concept Screening

This phase will consist of a series of designs, tests, design modifications, and retests to determine the best configurations for further evaluation, based on ability to use broad-specification fuels while meeting program exhaust emissions and performance goals and having suitable durability characteristics. Phase I is an eighteen-month effort and is currently in progress.

Phase II: Combustor Optimization Testing

This phase will consist of a series of tests, design modifications, and retests to establish the required overall combustion system performance, durability characteristics, and engine adaptability, utilizing the best designs of Phase I. Emphasis will be placed on interaction of the combustion system with other engine components. This phase is projected to take sixteen months.

Phase III: Engine Verification Testing

This phase will consist of steady-state and transient testing of the best combustion system(s) of Phase II as part of a complete engine. The projected length of this phase is sixteen months.

Program Schedule

The planned program schedule is shown in Table I. The Phase I contracts were awarded to the General Electric Company and Pratt & Whitney Aircraft in September and December, respectively, of 1979. This phase is scheduled to be completed in early 1981. Phase II is scheduled for completion in mid 1982, and Phase III near the end of 1983.

PROGRAM OBJECTIVES AND SPECIFIC GOALS

Program Objectives

The objectives of the NASA Broad-Specification Fuels Combustion Technology Program are:

1. To evolve and demonstrate the technology required to enable current and next generation high-thrust, high-bypass-ratio turbofan aircraft engines to utilize broad-specification fuels.
2. To verify the evolved technology in full-scale engine tests.

These objectives must be achieved within the existing and proposed emissions standards, within acceptable performance limits, and within acceptable combustion system durability limits. This requires that a number of specific program goals be met.

Specific Program Goals

Emissions Goals - The program emissions goals for the two reference engines, the General Electric CF6-80 and the Pratt & Whitney Aircraft JT9D-7, are shown in Tables II and III, respectively. In each case, the first column contains goals based on proposed Environmental Protection Agency (EPA) standards (reference 1) for engines manufactured after January 1, 1981, and which would apply to modifications to the baseline engine combustion system. The second column contains goals based on the proposed EPA standards for engines certified after January 1, 1984, and which would apply to the advanced combustion system concepts of this program.

Performance Goals - The program performance goals, applicable to all combustion system concepts, are given in Table IV.

Durability Considerations - Although no formal program goals have been set for combustor durability, a strong effort will be made to maintain production combustor design life. The primary indicator of expected liner life will be skin temperatures measured by thermocouples.

Program Fuels

The basic program fuel is the Experimental Referee Broad-Specification (ERBS) fuel established by the Jet Aircraft Hydrocarbon Fuels Technology Workshop (reference 2), convened at the NASA Lewis Research Center in June, 1977. This workshop involved representatives of the petroleum industry, engine and airframe manufacturers, airlines, the military, and NASA, with the purpose of establishing specifications for a reference fuel which would permit comparison of test results from numerous experimenters. The ERBS fuel specifications selected are contained in Table V. The most significant change relative to Jet A fuel is the increased aromatics content and, conversely, decreased hydrogen content, approximately 12.8 percent by weight, as compared with approximately 13.7 percent for Jet A.

In order that trends in emissions, performance, and durability characteristics with varying fuel hydrogen content can be assessed, two other ERBS fuels (Table V), with hydrogen contents of approximately 12.3 and 11.8 percent, will be used in the program. In addition, baseline testing will be conducted with Jet A fuel.

COMBUSTION SYSTEM CONFIGURATIONS

In combustion system designs, the potential for achieving the program goals and the technical risk involved are, more or less, proportional. Each contractor was required to design three combustion system concepts having varying levels of potential and risk. One concept, that having the lowest technical risk, was to involve relatively minor modifications to the production engine combustion system. The purpose of testing this concept is to determine the feasibility of modifying current in-use engine combustion systems to make them capable of using broad-specification fuels while meeting appropriate emissions requirements and maintaining the performance and durability characteristics of the production combustion systems. The second concept was to be a somewhat more advanced design, more likely to meet the program goals for engines certified after January 1, 1984, and having a correspondingly higher technical risk. This type of combustion system might be used in newly-manufactured engines, but would probably require sufficiently-significant engine design changes to preclude its use in older engines. The third concept was to be an even more advanced design, having high potential for meeting the program goals, but with a high anticipated level of developmental difficulty and risk. Such a combustion system might be used in a situation in which very strict emissions requirements are in effect, or in a situation in which fuel specifications must be significantly relaxed.

General Electric Designs

The engine selected as the reference engine for the NASA-General Electric program is the CF6-80 (figure 1), a somewhat shorter and lighter derivative of the CF6-50 engine. The combustion system being developed for the production CF6-80 is designed to meet the carbon monoxide (CO) and unburned hydrocarbons (HC) emissions standards proposed by the EPA for engines scheduled to be certificated prior to January 1. 1984.

Phase I testing will be conducted in a 60-degree sector test rig encompassing five fuel injectors. This test section is designed for testing at full CF6-80 sea-level takeoff pressure and temperature conditions. Although the test facility will not provide full pressure during the initial screening testing of Phase I, upgrading now underway will provide full pressure in the optimization testing in the latter part of Phase I.

Concept I - Single-Stage Combustion System

The initial configuration of this concept will be the production CF6-80 combustor (figure 2). Since this combustor is expected to meet the program emissions goals for in-use combustion systems using Jet A fuel, it is considered to be a low-risk design from that standpoint. Durability and fuel stability considerations may require some development effort. It is expected that adaptation to use with broad-specification fuels can be accomplished with relatively minor modifications to in-use engines.

Concept II - Double-Annular Combustion System

This concept (figure 3), developed in the NASA-GE Experimental Clean Combustor Program (references 3, 4, and 5), is considered to be a moderate-risk design. It consists of two separate annular passages. At low-power conditions, all of the fuel is injected into the outer annulus, the design of which is optimized for low CO and HC emissions. At high power conditions, most of the fuel is injected into the inner annulus, or main burning zone. Lean combustion is maintained in both annuli, with the outer annulus serving as a pilot zone, resulting in low smoke and oxides of nitrogen (NO_x) production. It is expected that the program goals for advanced concepts can be met for CO and HC using broad-specification fuels, but that the NO_x goal will be difficult to achieve.

Concept III - Single-Stage Variable-Geometry Combustion System

Variable-geometry combustors are intended to combine the better features of non-variable-geometry single-stage combustors and staged combustors. While the staged combustor provides a near-optimum primary-zone equivalence ratio at idle and takeoff conditions, non-optimum conditions prevail at intermediate power points, particularly at approach power, with the potential for causing emissions or stability problems. The variable-geometry combustor, on the other hand, can provide continuous modulation of airflow splits such that optimum equivalence ratios may be maintained over the range of operating conditions. If dilution-zone airflow is controllable in conjunction with primary-zone airflow modulation, combustion system pressure drop can be maintained as airflow splits are varied. If desired, pressure drop could be decreased, for instance at cruise, or increased to improve fuel atomization at ignition or altitude relight conditions. The variable-geometry combustor can also use a single fuel stage, at a great deal less expense than that incurred with staged combustors, and with a much-reduced potential for fuel-system coking relative to staged combustors, in which stagnant fuel remains in the main-stage fuel system during pilot-only operation. Disadvantages which must be weighed against these benefits are the increased cost and complexity introduced by the use of the mechanism required to vary combustor geometry in a reliable manner. The developmental risk associated with variable-geometry designs is in keeping with their high potential for meeting the program goals.

Figure 4 shows the variable-geometry combustor to be used in this program. It is somewhat schematic in nature, since the exact type of variation has not been determined; however, some form of variation in swirler effective area and/or swirler angle will be used. The objective will be to admit only approximately 20 percent of the total combustor airflow to the dome region at low-power conditions, and approximately 50 percent at high power. The velocity through the dome region at low power will be substantially reduced and, in conjunction with a high equivalence ratio, will result in low CO and HC. A much higher velocity and leaner burning will produce low NO_x at high-power conditions. At least one build of this combustor will have provision for varying dilution-zone airflow independently in order to balance total pressure drop as the primary-zone airflow is varied. This concept is expected to meet all program emissions goals for advanced combustors.

Pratt & Whitney Aircraft Designs

The reference engine for the NASA-P&WA program is the JT9D-7 (figure 5). The combustion system for this engine was designed prior to the present concern about engine exhaust emissions, and considerable design changes will be required in order to meet the CO and HC standards proposed by the EPA for engines scheduled to be certificated prior to January 1, 1984.

Phase I testing of Concepts I and III will be conducted in a 72-degree sector test rig with four fuel injectors, while Concept II testing will be done in a 90-degree sector rig in which six pilot-zone fuel injectors and 12 main-zone injectors will be used. This is because Concept II hardware will be borrowed from the NASA-P&WA Energy Efficient Engine Program. Testing of all concepts will be at full JT9D-7 pressure and temperature conditions.

Concept I - Single-Stage Combustor

This concept involves, in reality, two different combustors. The first is the present JT9D-7 production combustor (figure 6). This combustor was designed prior to the time when emissions became a matter of serious concern, and although it has a low smoke output, emissions of CO, HC, and NO_X are considerably above proposed standards. This combustor will undergo only one test, the purpose of which is to establish baseline data for the program that can be compared with in-service experience. This test will also provide an assessment of the impact of a near-term shift toward broad-specification fuels. The remainder of the Concept I tests will be conducted with a second single-stage combustor, the "Advanced Bulkhead" combustor concept, shown in figure 7. This combustor was designed with the intent of providing a combustor for the JT9D-7 series of engine models, capable of meeting the proposed EPA standards for CO, HC, and smoke emissions from engines manufactured after January 1, 1981.

The improvement in the emissions levels of the advanced bulkhead combustor relative to the reference JT9D-7 combustor is mainly attributable to a richer primary zone. The equivalence ratio of this combustor is approximately 1 at idle conditions, resulting in optimum consumption rates for CO and HC.

Concept II - Energy Efficient Engine (E^3) "Vorbix" Combustion System

This concept represents a "second-generation" design of a combustor evaluated under the NASA-P&WA Experimental Clean Combustor Program (references 6, 7, and 8). The present design, shown in figure 8, is currently being evolved under the NASA-P&WA E^3 Program. It is a staged design, with a primary zone optimized for operation alone at idle, and a main stage designed to minimize NO_X production at high-power conditions. The main stage fuel is injected through carburetor tubes (figure 9) for premixing with a portion of the main zone combustion air. This design, along with the large number of injectors, is intended to create a more homogeneous fuel-air mixture in the main zone, to reduce NO_X and smoke production. The location of the main-stage fuel injectors outside the combustor liner, in a cooler environment, may be advantageous in preventing potential fuel nozzle coking problems, expected to be more likely to occur when using broad-specification fuels having decreased thermal stability.

Concept III - Single-Stage Variable-Geometry Combustion System

Figure 10 shows the variable-geometry combustor to be evaluated in this program. It will use a single-pipe aerating fuel injector, and will have control mechanisms for both primary and dilution airflow. Control of fuel injector swirler airflow amount and flow angle will also be investigated. The interaction of this air with the fuel spray has been found to have significant effects on low power emissions, altitude relight characteristics, and high power smoke formation. The required control mechanisms, illustrated in figure 10, will not be designed and built during Phase I of this program. Instead, fixed-geometry configurations will be tested to assess the effects of variations in combustor airflow, and to define the required airflow schedule. The designing of the hardware needed to achieve this schedule will be addressed in Phase II of this program.

Combustor Modifications

In both programs, the initial build of each combustion system concept will undergo modifications and retesting to assess the effects of the various modifications on achieving the program goals. Although the modifications will take numerous forms, they can be grouped in three general classifications:

1. Modifications to airflow distribution to change either burning-zone equivalence ratio or aerodynamics.
2. Liner cooling revisions to lower liner temperatures or to minimize emissions.
3. Fuel injector changes to change droplet size or spray angle.

CONCLUDING REMARKS

Phase I of the program is now in progress with both contractors. Preliminary and final design tasks have been completed, and Task III, Fabrication and Installation, is now being accomplished. Phase I screening testing is scheduled for completion in early 1981, at which time contractor and NASA Lewis Research Center reports will be issued to describe test results and program progress and future plans.

REFERENCES

1. "Control of Air Pollution from Aircraft and Aircraft Engines - Proposed Amendments to Standards," Federal Register, Vol. 43, No. 58, March 24, 1978, pp. 12615-12634.

2. Longwell, J.P., Ed.; "Jet Aircraft Hydrocarbon Fuels Technology" NASA CP 2033, 1978.

3. Bahr, D.W.; and Gleason, C.C.: Experimental Clean Combustor Program, Phase I Final Report, NASA CR-134737, June, 1975.

4. Gleason, C.C.; Rogers, D.W.; and Bahr, D.W.: Experimental Clean Combustor Program, Phase II Final Report, NASA CR-134971, July, 1976.

5. Gleason, C.C.; and Bahr, D.W.: Experimental Clean Combustor Program, Phase III Final Report, NASA CR-135384, June, 1979.

6. Roberts, R.; Peduzzi, A.; and Vitti, G.E.: Experimental Clean Combustor Program, Phase I Final Report, NASA CR-134756, October, 1975.

7. Roberts, R.; Peduzzi, A.; and Vitti, G.E.: Experimental Clean Combustor Program, Phase II Final Report, NASA CR-134969, November, 1976.

8. Roberts, R.; Fiorentino, A; and Greene, W.: Experimental Clean Combustor Program, Phase III Final Report, NASA CR-135253, October, 1977.

TABLE I. - ANTICIPATED PROGRAM SCHEDULE

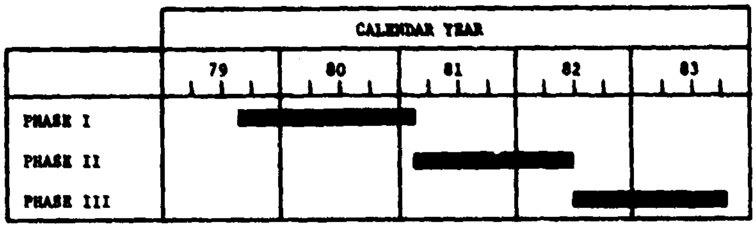

TABLE II. - CF6-80 DESIGN EMISSIONS GOALS

	FOR CONCEPT I - MODIFICATIONS TO BASELINE CF6-80 COMBUSTION SYSTEM	FOR CONCEPT II (DOUBLE-ANNULAR COMBUSTION SYSTEM) AND CONCEPT III (SINGLE-ANNULAR VARIABLE-GEOMETRY COMBUSTION SYSTEM)
HC	6.7	3.3
CO	36.1	25.0
NO_x	35.3*	33.0
SN	19.2	19.2

HC	TOTAL UNBURNED HYDROCARBONS (g/kn)
CO	CARBON MONOXIDE (g/kn)
NO_x	TOTAL OXIDES OF NITROGEN (g/kn)
SN	SAE SMOKE NUMBER

*Although no NO_x requirement is presently specified for engines manufactured prior to January 1, 1984, this goal is included to provide for the possibility that the combustion system developed for "in-use" engines might also be used on engines manufactured after that date.

TABLE III. - JT9D-7 DESIGN EMISSIONS GOALS

	FOR CONCEPT I - MODIFICATIONS TO BASELINE COMBUSTION SYSTEM	FOR CONCEPT II (E^3 VORBIX COMBUSTION SYSTEM) AND CONCEPT III (SINGLE-STAGE VARIABLE-GEOMETRY COMBUSTION SYSTEM)
HC	6.7	3.3
CO	36.1	25.0
NO_x	33.0*	33.0
SN	19.2	19.2

HC	TOTAL UNBURNED HYDROCARBONS (g/kn)
CO	CARBON MONOXIDE (g/kn)
NO_x	TOTAL OXIDES OF NITROGEN (g/kn)
SN	SAE SMOKE NUMBER

*Although no NO_x requirement is presently specified for engines manufactured prior to January 1, 1984, this goal is included to provide for the possibility that the combustion system developed for "in-use" engines might also be used on engines manufactured after that date.

TABLE IV. - DESIGN PERFORMANCE GOALS

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

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

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

TABLE V. - FUELS SPECIFICATIONS

Specifications	ERBS jet fuel value	ERBS12.3	ERBS11.8	Jet A
Composition:				
Hydrogen, wt%	12.8±0.2	12.3±0.2	11.8±0.2	ASTM D1655 - (latest specification) or equivalent
Aromatics, vol%	Report	Report	Report	
Sulfur, mercaptan, wt%	0.003, max	↕	↕	
Sulfur, total, wt%	0.3, max			
Nitrogen, total, wt%	Report			↕
Naphthalenes, vol%	Report			
Hydrocarbon compositional analysis	Report			
Volatility:				
Distillation of temperature, °F:				
Initial boiling point	Report			
10 percent	400, max			
50 percent	Report			
90 percent	500, min			
Final boiling point	Report			
Residue, percent	Report			
Loss, percent	Report			
Flashpoint, °F	100, min			
Gravity, API (60° F)	Report			
Gravity, specific (60/60° F)	Report			
Fluidity:				
Freezing point, °F	-20, max			
Viscosity, at -10° F, cS	12, max			
Combustion:				
Net heat of combustion, Btu/lb	Report			
Thermal stability:				
JFTOT, breakpoint temperature, °F	460 min			
(TDR, 13; and P, 25 mm)				

It is anticipated that ERBS12.3 and ERBS11.8 fuels will be obtained by the addition of suitable blending stock to ERBS fuel to reduce hydrogen content to 12.3 and 11.8 percent by weight, respectively.

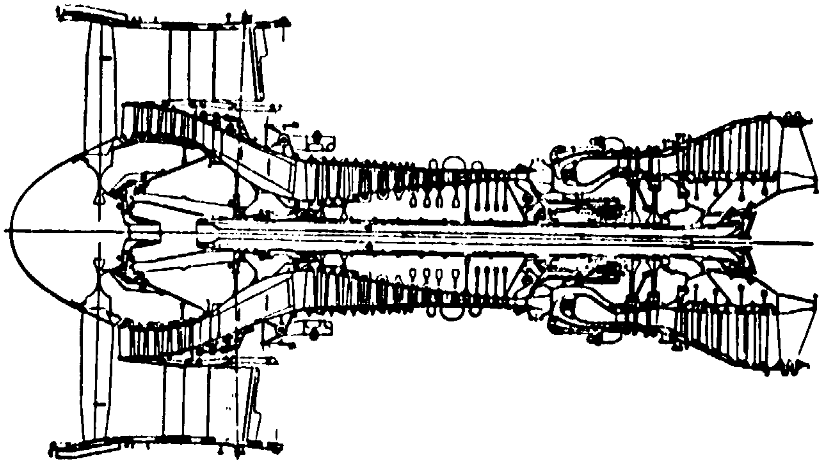

Figure 1. - CF6-80A reference engine.

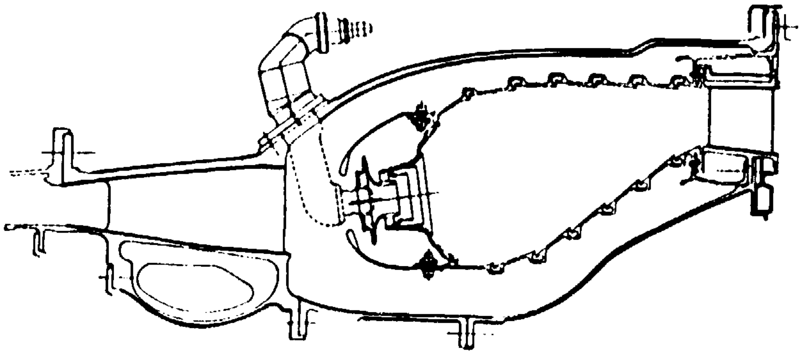

Figure 2. - CF6-80 Combustion system.

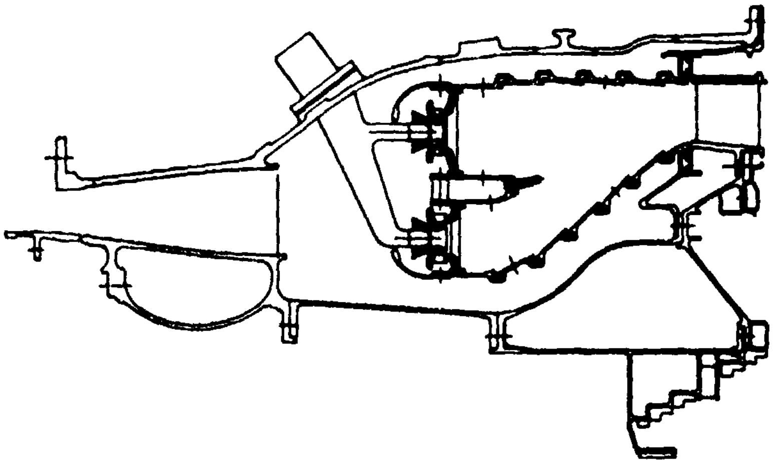

Figure 3. - CF6-80 Double-annular combustor concept.

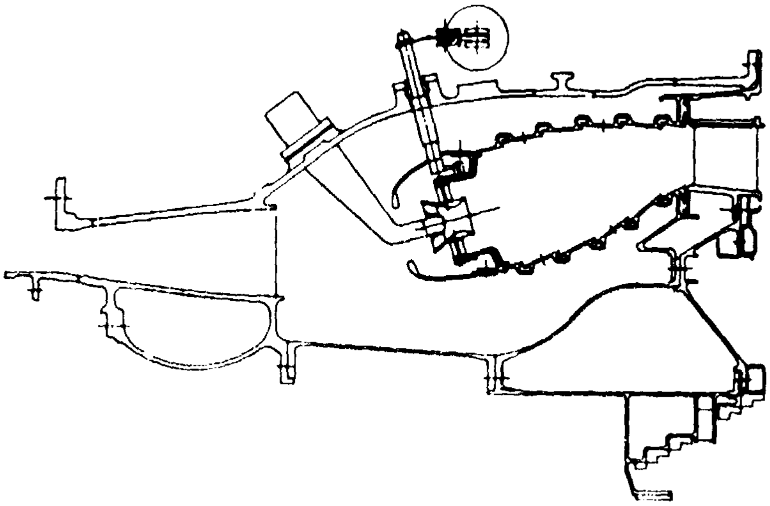

Figure 4. - CF6-80 Short Single-Annular Combustor Concept with Variable Geometry.

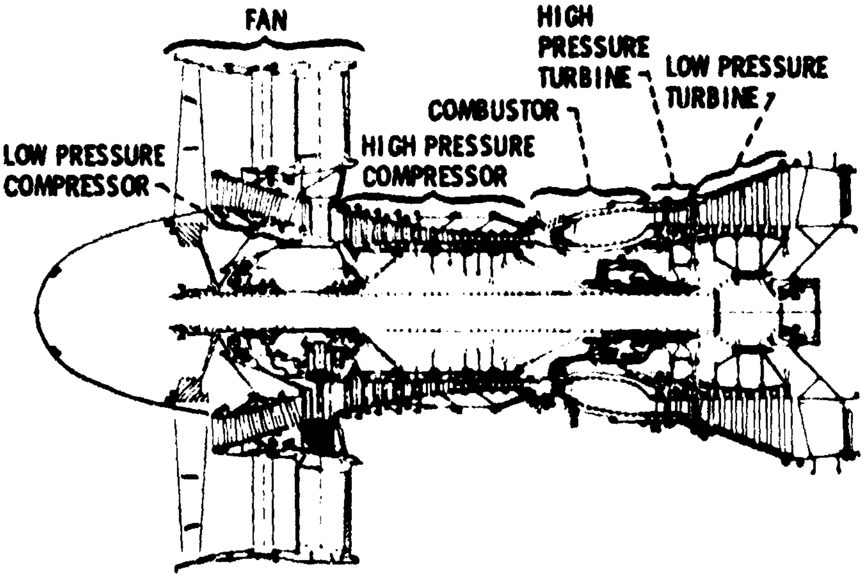

Figure 5. - Cross-section of the JT9D-7 reference engine.

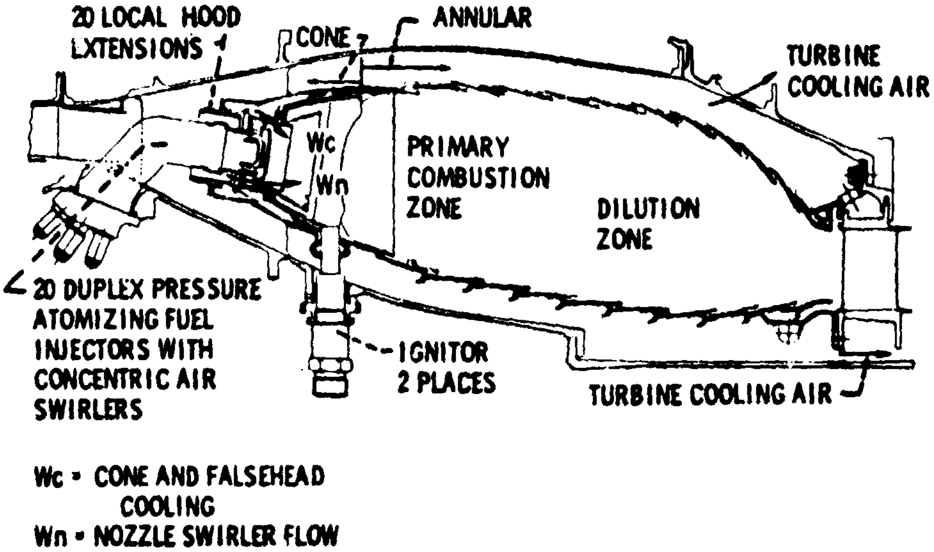

Figure 6. - Reference JT9D-7F combustor.

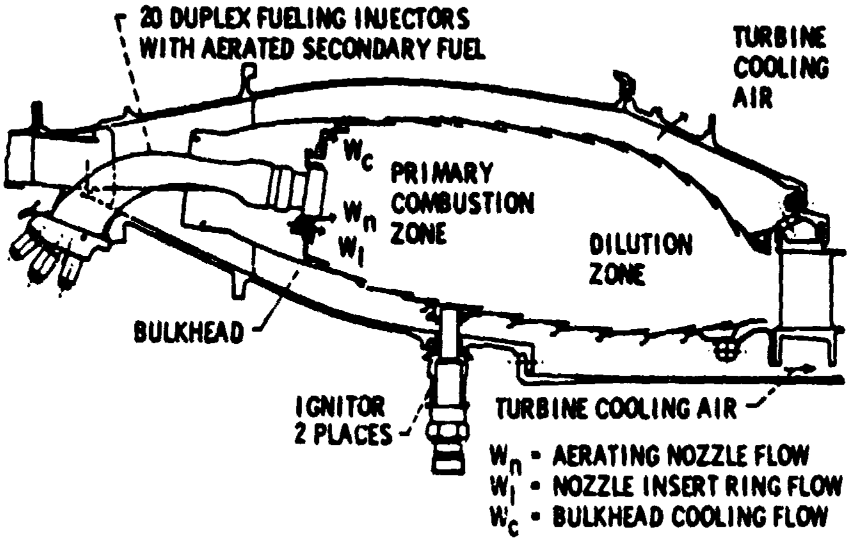

Figure 7. - Advanced bulkhead combustor concept.

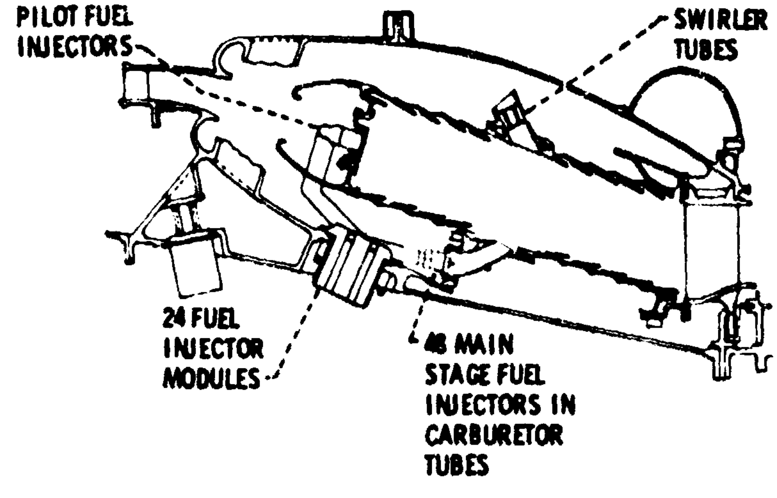

Figure 8. - "Vorbix" combustor designed for NASA-P&WA energy efficient engine program.

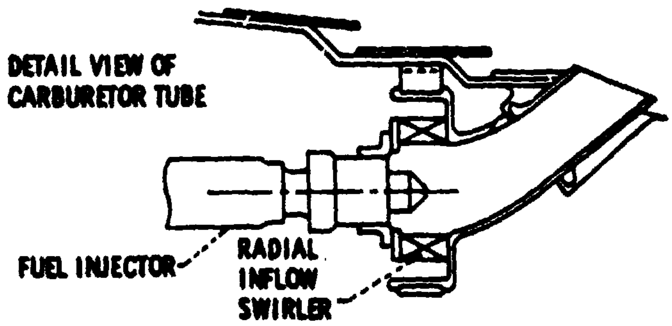

Figure 9. - Vorbix combustor carburetor tube.

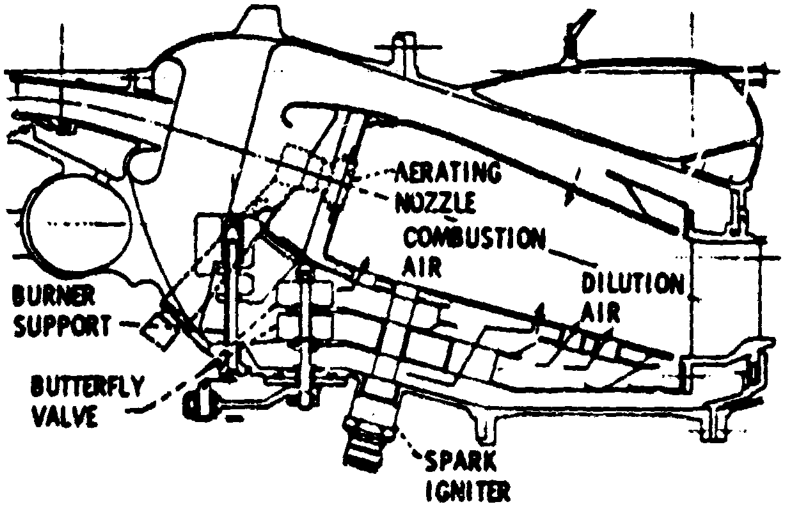

Figure 10. - Variable geometry combustor concept.