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The E^3 Combustors: Status and Challenges

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SUMMARY

The technology programs for the Energy Efficient Engine (E^3) combustors are outlined, status and test results to date are summarized, and present and future challenges indicated. The NASA-sponsored programs, which are being conducted at the General Electric Company and Pratt & Whitney Aircraft, are making important technology advances. Both combustor designs utilize an annular configuration with two-zone combustion for low emissions, advanced liners for improved durability, and short, curved-wall, dump prediffusers for compactness. Advanced cooling techniques and segmented construction characterize the advanced liners in both programs. Liner segments are made from castable, turbine-type materials. At this time, analysis and design activities have been completed; experimental evaluations are progressing. Test results are verifying both design concepts for combustion, cooling, and mechanical integrity. All goals appear capable of being met, with the exception of NO_x.

INTRODUCTION

The Energy Efficient Engine (E^3) Project is a NASA-sponsored endeavor which responds to the requirement for significantly reduced fuel consumption in the next generation of turbofan engines for commercial aircraft (ref. 1). The scope of the current effort, which began in early 1978, includes the analysis, design, fabrication, and testing of engine systems and components - which feature a multitude of advanced technologies. All activities are being conducted under contract with the General Electric Company (NAS3-20643) and Pratt & Whitney Aircraft (NAS3-20646). Goals of the project, which are referenced to current high-bypass ratio engines, include performance (SFC reduction of at least 12 percent and deterioration reduction of at least 50 percent); economics (DOC reduction of at least 5 percent); and environmental considerations (must meet noise and emissions regulations). These engine system goals translate into specific combustor component goals which are presented in table I.

Because the E^3 designs require high-pressure and high-temperature operating conditions for good performance (refs. 2 and 3), control of combustor emissions and design of durable liners are particularly challenging. A short combustor section length and simplicity were emphasized by engine design and goal considerations. These combustor technology programs provide significant contributions to the technology base. Such contributions are made by (1) extending the current research and technology (R&T) base (e.g., measurement and control of emissions at high pressures and high temperatures); (2) creating a new baseline for the technology base (e.g., design and evaluation of advanced liners for commercial engines); and (3) identifying new directions for future R&T efforts (e.g., advanced liner construction, materials, and cooling techniques).

To meet the extremely low emissions goals, the two-zone combustion approaches were selected for each combustor design. Prior efforts, which were sponsored by NASA in the Experimental Clean Combustor Program (ECCP), validated the two-zone concepts for emissions reduction and provided important design information (refs. 4 and 5). The E^3 combustor designs thus evolved from those in the ECCP at General Electric (GE) and Pratt & Whitney Aircraft (P&WA).

The ECCP focused on reducing emissions. In brief, a pilot zone controls low-power engine emissions of carbon monoxide (CO) and unburned hydrocarbons (HC), while a main zone controls the high power emissions of oxides of nitrogen (NO_x). Two-zone combustor design concepts were evaluated in component rig tests; eventually the best concepts were tested in full-size current engines. Because such engines provided more than sufficient length in which to insert the two-zone combustor concepts, the prediffuser, diffuser shrouds, and liner cooling were not optimized. Design simplicity and hardware durability also were not emphasized. In addition, most testing was performed at pressures significantly lower than those associated with the E^3 cycles.

While designs for the E^3 combustors have their basis in the ECCP designs, simplicity, durability, and other commercial engine considerations were stressed. Of particular importance is the fact that liner life analyses indicated that current technology, film-cooled, louvered liners fabricated in hoops of conventional combustor materials would not withstand the high-pressure, high-temperature combustion environments - let alone meet the liner life goals. Thus, advanced technology liner designs were required.

In table II are presented values of some of the E^3 combustor operating parameters at different points over the engine power range. Especially note the high pressures (P_{T3}) at SLTO, which tend to increase NO_x emissions; the high-temperature values of combustor inlet air (T_{T3}), which is used as the combustor liner coolant; and the high-combustor exit temperature values (T_{T4}), which indicate high thermal loads on the liners. The air which is delivered to the combustor is used for the combustion processes, for liner cooling, and for providing a low pattern factor. The more recent use of air to help reduce emissions has added to this demand for a limited supply of air. An argument can be made that, in some designs, air to control emissions has been obtained at the sacrifice of a proper liner cooling and pattern factor control; less durable liners and higher pattern factors have resulted.

Both E^3 combustor designs are annular and have short axial lengths, which reduce the surface area requiring cooling. The need for more efficient use of liner cooling air, however, became evident as the E^3 liner analyses progressed. Advanced - and more complicated - cooling schemes were screened from Independent Research and Development (IR&D) studies at both GE and P&WA. For the E^3 advanced liner design, the GE program selected an impingement-plus-film cooling (IPFC) scheme, while the P&WA program selected a counter-parallel Finwall (CPFW) technique. Moreover, to meet the respective life goals for the liners, both GE and P&WA programs chose to circumferentially and axially segment both the inner and outer liners. The effect is a substantial reduction in stresses (especially hoop) induced by the thermal environment experienced in combustors during normal modes of operation.

Finally, because of the difference in diameters between the compressor outlet and turbine inlet, the gas flowpath through the combustor had to be turned. Both the GE and P&WA designs use a short, curved-wall, dump prediffuser.

STATUS AND RESULTS

A schedule of activities required to evolve the E^3 combustors is shown in figure 1. The major activities include preliminary and detailed designs, model testing of the diffuser/combustor aerodynamics, sector combustor rig testing, full-annular combustor rig testing, and finally engine system evaluation.

Initially, both GE and P&WA programs conducted preliminary analysis and design activities to define the basic combustor configurations. Aerodynamic, thermodynamic, and mechanical design analyses were used. Such efforts defined the initial profiles of the prediffusers; number, type, and location of fuel injectors; combustor cooling requirements, techniques of liner construction, and initial locations for dilution airflows.

To evaluate, substantiate, and/or improve the basic combustor design configurations, tests were conducted in both GE and P&WA programs on parts of the combustor component. Cold flow testing included full-size, full-annular models of the prediffuser and simulated combustion chamber as well as pilot and main zone fuel injectors. Hot flow tests were performed with sector combustor rigs, which were no more than 90° of the full-annular configuration. An initial series of sector combustor rig tests followed the cold flow testing; thus, several design improvements were included. Such testing evaluated, in a combustion environment, ignition characteristics, staging of the pilot and main zone fuel injectors, altitude relight, emissions and smoke levels, liner cooling levels and hot spots, exit temperature profile, and pattern factor.

Results from the cold flow and initial series of sector rig tests were factored into the detailed design of the combustors. Starting with the basic combustor design configuration, such experimental results either substantiated the design or guided design modifications. In addition, more sophisticated analytical procedures were used to define the final combustor configurations.

At this time, all analysis and design activities, cold flow testing, and the initial series of sector combustor rig tests have been completed. Cross sections of the final combustor designs and their features are presented in figure 2(a) for the GE design and in figure 2(b) for P&WA.

Since the E^3 combustor designs evolved from those in the Experimental Clean Combustor Program and potentially are the next generation beyond current production combustors (namely, those in the CF6-50 and JT9D-7 engines), it is interesting to make some comparisons. Figure 3 shows the evolution of the GE and P&WA combustors from current designs, to ECCP designs, and finally the E^3 designs. The cross sections have been scaled to the same axial dimension indicated. For the E^3 combustors, the very short axial lengths are readily apparent, as is the simplicity in designs relative to those from the ECCP.

It is an intent of the E^3 programs to present definitive information from specific activities as they are completed. Such information is published in NASA Contractor Reports. In addition, some results are being presented in professional technical society meetings and publications (e.g., see refs. 6, 7, and 8).

One purpose for this paper is to provide an overview of all E^3 combustor activities and, thus, serve as a reference for the more definitive contractor reports and society publications. Another purpose is to present - for designs and experimental evaluations to date - a brief description, highlights of test results, and the status of technical accomplishments relative to the goals. The sections which follow present such descriptions, results, and status of the cold flow tests, advanced liner design and fabrication, and initial series of sector combustor rig testing. In addition, the GE program currently is testing a full-annular combustor rig configuration; this activity also is presented.

Diffuser/Combustor Model Testing

Design of the annular flowpath from the compressor exit guide vanes to the combustor exit had the objectives of (1) a short length prediffuser, (2) separation-free flow in the curved-wall prediffuser prior to dumping into the downstream diffuser/combustor section, and (3) insensitivity to inlet flow profile variations, axial location of the combustor hood, flow splits around and through the hood, and cooling air bleeds. Pressure loss goals are noted in table I. To experimentally evaluate the aerodynamic performance of the basic combustor design configurations, tests were conducted using full-size, full-annular models of the diffuser/combustor systems. The models were constructed from Plexiglas and wood, and they were instrumented primarily with static and total pressure probes.

The P&WA model test rig is shown schematically in figure 4. Several variations of the prediffuser wall profile - in terms of angle of flow turning, length, and diffuser area ratio - were evaluated. In addition, the dump gap between the prediffuser exit and hood was varied as was the gap between the hood and diffuser case in both the inner and outer annuli. Most design variations were evaluated using three different inlet flow profiles; that is, peaked toward the outer diameter, the center, and the inner diameter. Following several improvements to the basic design, confirmation was established for a final design which met all objectives. Table III lists some of the geometric and operational characteristics of the design. It is evident that the prediffuser pressure loss met the goal. In addition, the almost constant values for the static pressure recovery coefficient (C_p) along the prediffuser walls as the inlet profile changed indicate insensitivity to inlet flow variations. Further details of this completed effort may be found in references 6 and 9.

For the GE design, the split duct prediffuser profile was evaluated initially using a three-times scale, two-dimensional model, and a water table. Purpose of such testing was to identify a preferred prediffuser shape which did not exhibit potential flow separation or instability. The final shape is shown in figure 5, along with the inlet and outlet Mach numbers, flow splits, and streamlines. The area ratio between the two exit passages and the inlet is 1.8.

The full-size, full-annular diffuser/combustor model test rig used in the GE program is shown in figure 6. Tests were conducted initially with three different inlet flow profiles. However, subsequent testing of the E^3 compressor component established that the inlet velocity is actually between the center and the inner peaked profiles. Table IV presents some of the operational characteristics of the final design for the above inlet flow profiles. As can be seen, the pressure losses did not quite meet the goal levels; however, the losses are low relative to a single path prediffuser design and are acceptable for the engine system. Unlike the single path prediffuser, the flow through this split duct prediffuser exhibited some sensitivity (based on C_p changes) to inlet flow profile. Further details of this completed effort may be found in reference 7.

Fuel Injector Characterization Testing

Good atomization of the fuel is required for proper ignition characteristics, high combustion efficiencies, and low emissions in combustors operated over the range of engine operating conditions, from ignition, to idle, and up to sea-level takeoff (SLTO). Measurements or calculations of pressure drops, flow rates, and velocities, effective flow areas, spray cone angles, swirl strengths, and droplet sizes are used to characterize fuel injectors and rate their atomization quality relative to one another.

The fuel injectors used in the E^3 combustor programs were designed and initially characterized by specialized vendors according to specifications provided under the programs. In the GE program, two vendors provided two competing fuel injector designs for the pilot combustion zone and likewise for the main zone. Both pilot and main zone injectors were basically pressure atomizing types and used counter-rotating air swirlers (fig. 2(a)) for good atomization with acceptable pressure drops. The P&WA program similarly used two vendors but only for the pilot zone injector designs. A single pipe aerated nozzle type with co-rotating swirlers was specified.

Following cold flow acceptance testing, each of the injector designs was evaluated in hot flow sector combustor rig tests. Evaluations were based primarily on ignition characteristics and emissions levels of the combustors. The better of each of the competing designs was used for further characterization in sector combustor rig testing as well as the design for the full-annular combustor. As discussed in a following section on sector combustor rig test results, the selected injector designs provided acceptable ignition characteristics, combustion efficiencies, and low emissions.

The P&WA program evolved a carburetor tube type injector, shown in figure 7, for the main combustion zone. Briefly, a Simplex pressure atomizing type injector sprayed a fuel cone into a converging, curved-wall tube in which air was swirled from a radial inflow swirler located in the same axial plane as the Simplex injector. Cold flow visualization tests showed that the fuel formed a thin film, on the inside wall of the tube, which flowed toward the tube exit into the main combustion zone. Final atomization occurred at the exit lip of the tube. Atomization quality, which was characterized by droplet measurements using laser/computer instrumentation, is presented in figure 8. As shown in the figure, droplet size in terms of Sauter Mean Diameter (SMD) can be controlled by fuel flow rate, tube core velocity, and airflow rate through the sleeve surrounding the tube exit. The carburetor tube concept was investigated initially under an IR&D program which indicated the potential for low NO_x and smoke. The E^3 sector combustor rig tests further confirmed these benefits and also showed low pattern factor characteristics. Further improvements in the op- eration of the carburetor tube are anticipated by the use of a co-rotating swirler in the outer sleeve design for the full-annular combustor.

Segmented Liners: Design and Fabrication

Combustor liners for current engines are constructed from hoops of conventional combustor materials (e.g., Hastelloy-X, Haynes-188, etc.) which are stacked axially to form a louver-like profile. Air injected between the louvers flows over the hot surface to cool and limit the wall temperature. As engine operating temperatures have been increased for improved performance and as emissions control has, in effect, reduced the amount of air available for cooling, the durability of such liners has been decreased.

Both E^3 combustors initially were designed to the above traditional approach. And both fell far short of the aggressive liner life goals (see table I) of the high-pressure and high-temperature Energy Efficient Engines.

A primary contributor to the short-life predictions was high hoop stresses. Accordingly, by dividing each hoop into a number of sections, or segments, stresses were reduced and life increased. Segmented construction, in turn, opened the door to alternate materials which had higher melting temperatures and, in some cases, could be cast. Finally, implementation of alternate cooling techniques, which were more thermally efficient and required less air for combustor cooling, completed the break from conventional liner design.

The P&WA E^3 combustor design features the inner and outer liner walls sectioned both circumferentially and axially. The inner liner is constructed from 48 separate segments; 24 segments of one design are used in the pilot combustion zone, while 24 segments of a second design are used in the main zone. The outer liner is constructed similarly but, in addition, has mid-segments at the axial locations of the main zone injectors. Thus, a total of 120 segments, representing five designs, are required to form the liners. Each design features a specific overall length and two, three, or four panels (akin to hoop sections) depending on thermal loads. An isometric view of typical inner and outer liner segments is shown in figure 9.

Several additional features of the P&WA design are illustrated in figure 9. First, air leakage between adjacent segments was minimized by feather seals which were captured in thin slots along the edges of each segment. Second, an advanced cooling technique was incorporated in the design. The technique, called counter-parallel Finwall (CPFW), features for each panel convection cooling between the integrally constructed hot and cold walls, followed by film cooling of the hot surface. Each CPFW cooling channel measures 0.089 cm (0.035 in.); hot and cold walls were approximately 0.102 cm (0.040 in.). Maximum channel length which had to be "drilled" was 5.72 cm (2.25 in.)

Liner segments were cast to near net shape from B1900+Hf. This turbine-type material is a nickel-base casting alloy, which is durable at high temperatures (up to 1800° F). Edges were ground, while feather seal and coolant inlet slots were electro-discharged machined (EDM). State-of-the art fabrication technology was applied to accurately "drill" the closely spaced, small diameter cooling channels while maintaining uniform hot wall thickness. Figure 10 shows the "drilling" process successfully used - electro-chemical machining (ECM).

To form the inner and outer liners, the segments were attached by integral hooks to open gridwork structural frames made from Hastelloy-X. the array of segments thus were allowed to "float in place" on the frame as thermal loads varied. The structural frames are indicated in figure 2(b) and illustrated in a figure which follows. The P&WA segmented liner is discussed further in reference 8.

The GE E^3 combustor design similarly features the inner and outer-walls sectioned by circumferentially and axially. The inner liner is constructed from 45 separate segments; there are 15 circumferential segments in each of the three axial locations. The outer liner is constructed from 60 segments, arranged in three axial groupings each having 20 segments. Thus, a total of 105 segments are required to form the liners. Judicious arrangement of the segments illustrates the axially in-line joints between circumferentially adjacent segments and, thus, forms a "Shingle" pattern. A typical inner liner having the Shingle constructin is shown in figure 11(a).

Whereas the P&WA segmented liner is a first generation design. The GE design is second generation. Prior to the NASA E^3 Project, the Air Force and Navy sponsored segmented liner technology at GE under the Advanced Turbine Engine Gas Generator (ATEGG) Program. In these initial efforts, feather seals were used to minimize air leakage between segments. Efforts in the E^3 program eliminated the 105 feather seals by the use of lap joints. In addition, the total of 105 segments represents a reduction from 160 segments used in the prior effort. An impingement-plus-film cooling technique (IPFC) was used. Consequently, the hot and cold walls were not integrally constructed. Liner segments were cast to near net shape from X-40 material and ground to final dimensions. X-40 is a turbine-type casting alloy which has a cobalt base and high temperature (up to 1800° F) durability. Segments were attached by an unique hook design to a structural shell of INCO 625, which was perforated with a multitude of small holes to provide impingement cooling on the outside of each segment. Individual segments, associated feather seals, and the perforated structural shell also are shown in figure 11(a), while the lap joint replacement for the feather seals is depicted in figure 11(b).

At this stage of liner development, both the GE and P&WA programs are predicting liner life values well in excess of three-times the respective goal levels. Experimental tests to date have confirmed the temperature and cooling flow estimates used in making life predictions. Further evaluations are planned using full-annular combustors with the advanced liners in rig and engine system tests.

Sector Combustor Rig Testing

To evolve simplified, two-zone, annular combustors, preliminary designs were evaluated and developed in hot flow sector combustor rigs. In the GE program, a 77° - sector combustor with conventional film-cooled louver liners was used. Test pressures were rig-limited to less than 6.8 atm (100 psia). The P&WA program featured two configurations of a 90° - sector combustor. One configuration had conventional film-cooled louver liners, with testing limited to 15 atm (220 psia). The louver liner combustors of GE and P&WA were used to evaluate the effects of fuel injector design and airflow scheduling on combustion efficiency, emissions, combustion staging from one-to-two zone operation, ignition, altitude relight, pattern factor, and radial temperature exit profile. The second P&WA configuration had segmented liners and was tested at pressures up to 30.2 atm (445 psia) (SLTO condition). This configuration is shown in figure 12.

Emissions levels for the above combustors, as well as those for current and ECCP combustors, are presented in table V. While this provides a comparison of emissions reduction efforts from the reference current engines, to the ECCP final configurations, to the E^3 program results from the above testing, care should be used in making any absolute conclusions. The current and ECCP emissions results are from full-annular combustors tested in engines, while the E^3 results are from sector combustor rig testing. The trend toward lower emissions from using two-zone combustors seems evident, however, when the ECCP and E^3 program results are compared with current combustor results. It should be noted that margins for development and variability have been added to the ECCP and E^3 experiment data. This provides more realistic comparisons with current production engines. In general, the E^3 emissions of carbon monoxide (CO) and hydrocarbons (HC) show significant reductions and either meet the program goals or are very close.

While oxides of nitrogen (NO_x) emissions have been reduced as well, the present status (EPAP equal to 4.7) does not meet the program goal (3.0). Since NO_x generation increases with pressure, the high-pressure operating conditions for the E^3 combustors is particularly challenging.

As shown in table V, the levels of smoke were excessively high in the ECCP. Refinements in the two-zone combustor designs for the GE and P&WA E^3 programs reduced the smoke levels to meet the program goal. Particularly noteworthy was the effect of the P&WA program's carburetor tube design. Sector combustor rig testing usually indicated smoke levels of less than one (SAE number) to a maximum of four. In addition, low pattern factors were consistently measured, with the present status being 0.26 (goal of 0.37).

Results of sector combustor rig testing to date have been encouraging. Combustor designs have been substantiated; the evaluated effects of fuel injector design and airflow scheduling indicated fundamental soundness of the designs. Evaluations of the P&WA segmented liners, over the E^3 power range of operation, shows measured cooling flows and wall temperatures being close to predicted values and support liner life predictions of three times the program's goal. Based on prior efforts in the ATEGG program, the GE E^3 program liner life predictions are similar to those of P&WA.

Full-Annular Combustor Rig Testing

The preliminary and detailed design activities and the sector combustor rig tests to date, in both the GE and P&WA programs, have defined full-size, full-annular combustor baseline design configurations for subsequent fabrication and experimental rig evaluations. In the P&WA program, fabrication of this baseline combustor is currently in progress; testing is expected to start in the fourth quarter of 1981. The approach in the GE program is to fabricate not only the baseline combustor with the segmented liner construction but, also, to fabricate a simpler, more easily modified machined ring liner experimental combustor. This experimental combustor matches the aerodynamic flowpath and airflow distributions inside the advanced liner combustor. At this time, the GE program has fabricated and tested this experimental combustor as well as one modification (Mod 1).

In the GE program, two types of full-annular combustor tests are being conducted. High-pressure tests are used to evaluate emissions, performance, and durability characteristics of the combustor for various simulate operating conditions ranging from idle-to-takeoff. Exhaust emission levels of carbon monoxide (CO), unburned hydrocarbons (HC), and oxides of nitrogen (NO_x) are measured during such tests. In testing to date, the measured emissions levels for the baseline experimental combustor and the Mod 1 combustor configurations are shown in table VI. The significant design changes incorporated in Mod 1 were an enriched pilot zone, which was accomplished by reducing the swirl cup airflow and the primary dilution airflow; and a leaner main zone, which was accomplished by increasing the swirl cup airflow. In general, the emissions results from the Mod 1 experimental combustor are encouraging. Additional refinements should provide further emissions reductions during testing of the segmented liner combustor configuration. An anticipated reduction in the CO and HC emissions levels will be made by further enriching the pilot zone through reduction of the airflow.

In the second type of testing performed in the GE program, atmospheric pressure tests are conducted to develop uniform combustor exit gas temperature distribution and ground start capabilities. Figure 13 illustrates the

GE E^3 experimental combustor during an atmospheric pressure test. The measured maximum and average radial temperature profiles for the baseline and Mod 1 configurations of the experimental combustor are shown in figure 14. As shown in the figure, the Mod 1 configuration of the experimental combustor comes very close to meeting all the temperature profile goals at the takeoff condition, where both the pilot and main zones are operating. A small increase in the inner liner dilution airflow will be incorporated in the segmented liner combustor configuration to trim the radial temperature profile near the inner wall.

As shown in table VI and based on the above full-annular experimental combustor results, the GE program projects that the final segmented liner combustor will meet or come close to meeting all the E^3 program combustor goals.

CONCLUDING REMARKS

The combustor designs for the General Electric and Pratt & Whitney Aircraft Energy Efficient Engines are markedly different from the reference (current) engine combustors with respect to several features. The most obvious change is the E^3 programs' use of two-zone combustion for reduced emissions. This combustion technique is an evolutionary extension of technology from the NASA Experimental Clean Combustor Program's concept verifications. Another and perhaps more significant change at this time is the use of more efficient cooling techniques and segmented construction for more durable liners. While such advanced liners or elements of them have been investigated in recent efforts under the ATEGG program and IR&D programs, the E^3 program investigated their application to commercial aircraft engines.

At this time, cold flow testing of the diffuser/combustor aerodynamics and fuel injector characteristics have been completed. Hot flow testing of sector combustor and full-annular combustor rigs is continuing. Test results to date are very promising with regard to meeting the goals shown in table I. The following briefly summarizes some of the results and the status of the E^3 combustor technology programs: Evaluations of the diffusers indicate overall pressure losses between 5.0 and 5.5 percent of the combustor inlet pressure as well as stable flow for a range of inlet flow profiles, with the goals thus being met; fuel injectors have been characterized in both cold flow and combustor rig tests and have shown acceptable performance for ignition, high combustion efficiencies, and low emissions; sector and full-annular combustor rig testing have shown (1) a strong potential for meeting the CO and HC emissions goals but most likely not meeting the goal for NO_x, (2) low smoke levels (4-10) and low pattern factors (about 0.25) which meet the goals, and (3) segmented liner designs which exhibit mechanical integrity and potential for life of three-times the respective goal values.

Future generations of large turbofan engines for commercial aircraft must exhibit reduced fuel consumption. Engine fuel consumption may be reduced by improving the efficiency of each component and/or the engine operation cycle. Better cycle efficiency, however, leads to higher operating pressures and temperatures. There have been recent projections of future engines having a design overall pressure ratio of up to 45-to-1 (ref. 10); growth versions of the E^3 designs approach this value (ref. 11). Thus, control of emissions (especially NO_x) and providing acceptable liner durability will remain as technology challenges.

Future standards for emissions from such engines are being reassessed by the U.S. Environmental Protection Agency (EPA). The inherently increased generation of NO_x at the higher pressures (that are needed for improved fuel economy) and practical limitations to control NO_x are of particular concern. The E^3 program emissions goals, which in 1977 were based on the proposed EPA 1981 standards, are very stringent. Although the NO_x goal may not be met, a general opinion is that the levels predicted to be finally achieved will meet future standards. Consequently, any efforts to further evolve the two-zone combustors should focus on simplifications which lead to reduced complexity, weight, and cost, while not increasing emissions.

The demand for more efficient utilization of combustor air for cooling will continue as engine operating temperatures are increased. The E^3 combustor designs, which use impingement-plus-film (GE) and counter-parallel Finwall (P&WA), are improvements over the more traditional film cooling. There are other techniques (e.g., ref. 8), however, which are either more thermally effective or less difficult to fabricate and should be evaluated further. Also, the use of higher temperature materials can alleviate some of the cooling requirements. Oxide dispersion strengthened (ODS) alloys are an example; they presently are being investigated in another NASA-sponsored program (ref. 12). Minimizing liner surface areas, of course, reduces cooling requirements. The short E^3 combustor lengths inherently have less liner surface areas to cool when compared with the reference combustors. The trend to shorter combustor sections will continue, since it is influenced by reduced weight and performance deterioration benefits to the engine system.

The E^3 programs are providing new technology for segmented combustor liner construction for application to commercial aircraft engines. Segmenting combustion chamber walls to improve durability, it should be noted, has been studied for at least the past 25 years. NASA-Lewis aeronautics research in the 1950's (refs. 13 to 15) evaluated several segmented liner designs to improve durability of aircraft engines. The technology of segmented combustor liners for commercial aircraft, however, is at a relatively early stage of development; a common experience is increased weight and fabrication costs relative to conventional liners. The challenge is to reduce both.

While life (durability) of segmented combustion chamber walls is usually analytically predicted to be much greater than hoop-type designs, actual experience is very limited; durability testing is needed. It may be hypothesized, however, that past experience with aircraft turbine engines, as to conditions for replacement of hoop-type liners, may no longer apply with segmented liners. For example, the P&WA segmented liner design could experience a crack in the hot wall, while the structural cold wall remains intact. Also, the very nature of the segmented wall design would limit crack propagation to a specific length. And a crack along the hot-wall side of a CPFW channel may be arrested by the release of extra cooling air.

Segmented liner construction for commercial aircraft engines is also significant because of the new possibilities for materials, fabrication, and maintenance. The potential exists for reduced costs and weight and use of nonstrategic materials, which is of increasing importance (ref. 16). Both E^3 combustor designs use high-temperature, turbine-type materials and casting for fabrication. Liner design simplifications and more aggressive casting hold the potential for mass production of liner segments, which should reduce costs. Finally, segmented construction allows consideration of another high-temperature but brittle liner material - ceramics. At the present time, a government-sponsored program (ref. 17) is experimentally developing segmented ceramic liner technology. Such a liner for commercial aircraft engines would be perhaps the most challenging endeavor but should be considered for its many benefits.

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TABLE I. - GOALS FOR THE GE AND P&WA ENERGY EFFICIENT ENGINE COMBUSTORS

	GE	P&WA
Section pressure drop, percent P_{T3}	5.0	5.5
Diffuser	1.5	3.0
Liners	3.5	2.5
Emissions (EPA-1981 proposed standards)		
CO, EPAP[a]	3.0	3.0
HC, EPAP[a]	0.4	0.4
NO_x, EPAP[a]	3.0	3.0
Smoke, SAE number	20.0	20.0
Life for liners (to first repair)		
Time, hr	9000	8000
Cycles	9000	4900
Pattern factor (maximum)	0.25	0.37
Acceptable radial temperature exit profile, sea level starting, altitude relight, and acceleration time.		

[a] EPA parameter (EPAP) in pound pollutant/K pound thrust hour/cycle.

TABLE II. - OPERATING CONDITIONS PERTINENT TO ENERGY EFFICIENT ENGINES AND COMBUSTORS

Operating conditions	Units	GE					P&WA				
		Ground idle	Approach	SLTO	Maximum climb	Maximum cruise	Ground idle	Approach	SLTO	Maximum climb	Maximum cruise
Net thrust, F_N	kN (lb)	9.9 (2221)	46.5 (10 450)	162.3 (36 496)	40.2 (9040)	37.5 (8425)	11.3 (2536)	37.3 (8374)	160.8 (36 156)	43.0 (9664)	38.4 (8626)
Overall pressure ratio, OPR	---	4.3	15.0	29.9	37.9	36.0	4.3	12.7	30.2	40.5	37.4
Combustor inlet pressure, P_{T3}	atm (psia)	4.3 (63)	15.2 (223)	29.9 (439)	13.6 (200)	12.9 (190)	4.3 (63)	12.5 (183)	30.2 (445)	14.6 (214)	13.4 (197)
Combustor inlet temperature, T_{T3}	K (°F)	497 (434)	678 (760)	815 (1007)	766 (919)	752 (893)	473 (391)	656 (721)	806 (991)	767 (921)	748 (886)
Combustor exit temperature, T_{T4}	K (°F)	958 (1264)	1243 (1777)	1619 (2454)	1572 (2370)	1533 (2299)	846 (1063)	1259 (1806)	1637 (2487)	1595 (2411)	1542 (2315)
Combustor airflow, W_{36}	kg/sec (lb/sec)	10.2 (22.5)	32.0 (70.5)	55.2 (121.7)	25.6 (56.4)	24.6 (54.3)	11.6 (25.5)	27.2 (60.0)	57.5 (126.7)	28.1 (61.9)	26.4 (58.2)
Fuel/air ratio	---	0.0110	0.014	0.022	0.022	0.021	0.0098	0.015	0.025	0.023	0.024
Combustor efficiency	Percent	0.9887	0.9950	0.9950	0.9950	0.9950	0.9878	0.9995	0.9995	0.9995	0.9995

TABLE III. - GEOMETRIC AND OPERATIONAL CHARACTERISTICS OF THE P&WA E^3 DIFFUSER DESIGN

Prediffuser geometry	
Length/radial inlet height	3.5
Area ratio	1.5
Turning angle	14°
Inlet Mach number	0.28

Operational characteristics	Inlet profile		
	ID-peaked[a]	Center-peaked	OD-peaked
Prediffuser static pressure recovery coefficient (C_p)			
ID wall	0.47	0.46	0.45
OD wall	.35	.35	.34
Flow splits[b], percent W_{36}			
ID	22.8	21.2	20.7
OD	58.5	59.6	60.6
Hood	18.7	19.2	18.7
Exit Mach number	----	----	0.176
Prediffuser total pressure loss, percent P_{T3} (goal = 3.0)	2.6	2.7	2.5

[a] Experience profile

[b] Without cooling air bleed extraction.

TABLE IV. - GEOMETRIC AND OPERATIONAL CHARACTERISTICS OF THE GE E^3 DIFFUSER DESIGN

Prediffuser geometry	
Length/radial inlet height	3.23
Area ratio	1.8
Inlet Mach number	0.30
Number of structural struts	30

Operational characteristics	Inlet profile		
	ID-peaked	Center-peaked	Goal
Prediffuser static pressure recovery coefficient (C_p)			
ID	0.55	0.48	
OD	.55	.48	
Flow splits, percent W_{36}			
ID	52	----	
OD	48	----	
Exit Mach number	0.16	----	
Total pressure losses in various passages of the airflow model, percent P_{T3}			
Outer passage	2.47	3.06	2.5
Outer dome	1.43	1.21	0.8
Center passage	1.21	1.88	3.0
Inner passage	1.44	2.08	2.2
Inner dome	1.08	1.44	0.8
Weighted average	1.17	1.81	1.5

TABLE V. - EMISSIONS LEVELS FOR GE AND P&WA COMBUSTORS

	Emissions[a]			
	CO	HC	NO_x	Smoke
Current engines				
GE (CF6-50C)	10.8	4.3	7.7	13
P&WA (JT9D-7A)	10.4	4.8	6.5	4
Experimental clean combustor program				
GE[b]	7.3	.4	6.2	25
P&WA[b]	4.3	.3	3.3	30
Energy efficient engine program (status)				
GE[b] (sector combustor rig/conference V)	4.1	.52	4.7	--
P&WA[b] (sector combustor rig/initial test series)	2.3	.38	4.7	4

[a] CO, HC, NO_x in EPAP units; smoke in SAE units.
[b] Margins added for development and variability.

TABLE VI. - STATUS OF TESTING THE GE E^3 FULL-SIZE, FULL-ANNULAR COMBUSTOR

	Baseline	MOD I	Projected E^3 combustor	Goal
CO, EPAP[a]	9.5	5.22	2.8	3.0
HC, EPAP[a]	4.2	.8	0.07	.4
NO_x, EPAP[a]	3.1	3.1	2.9	3.0
Smoke, SAE number	10.0	10.0	15.0	20.0
$\Delta P/P$, percent	5.0	6.0	5.0	5.0

[a] EPAP in pound pollutant/K pound thrust hour/cycle. Margins added for development and variability.

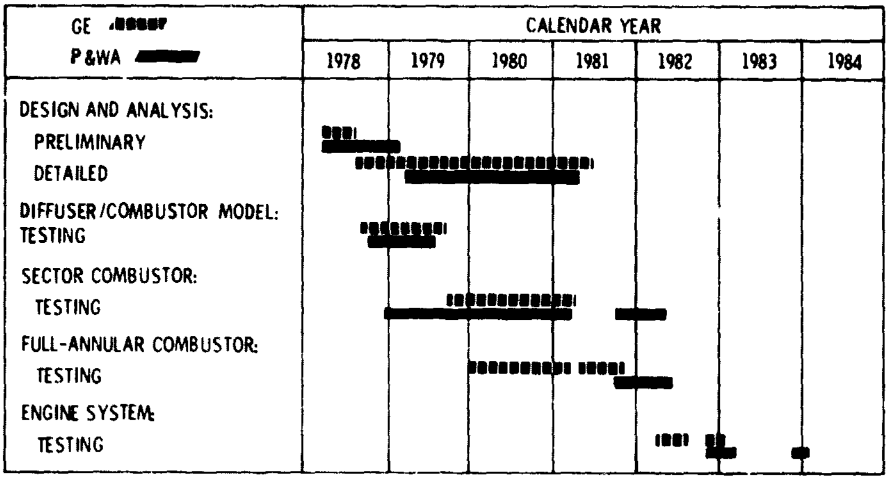
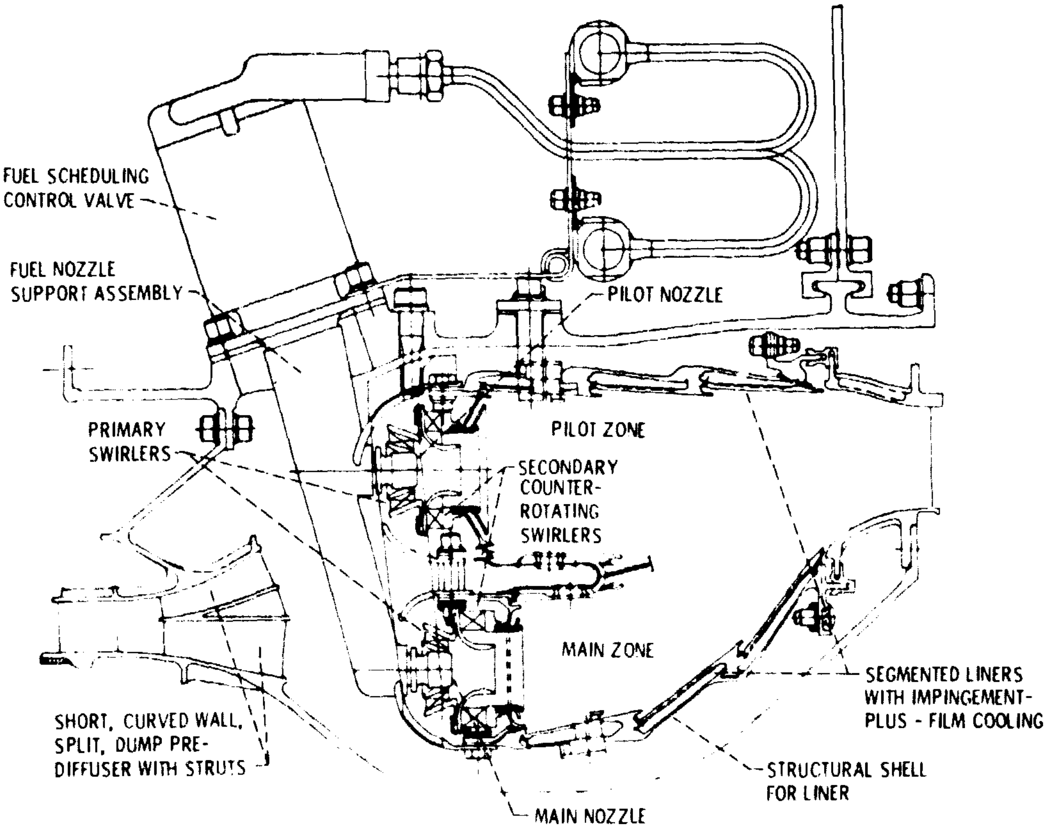
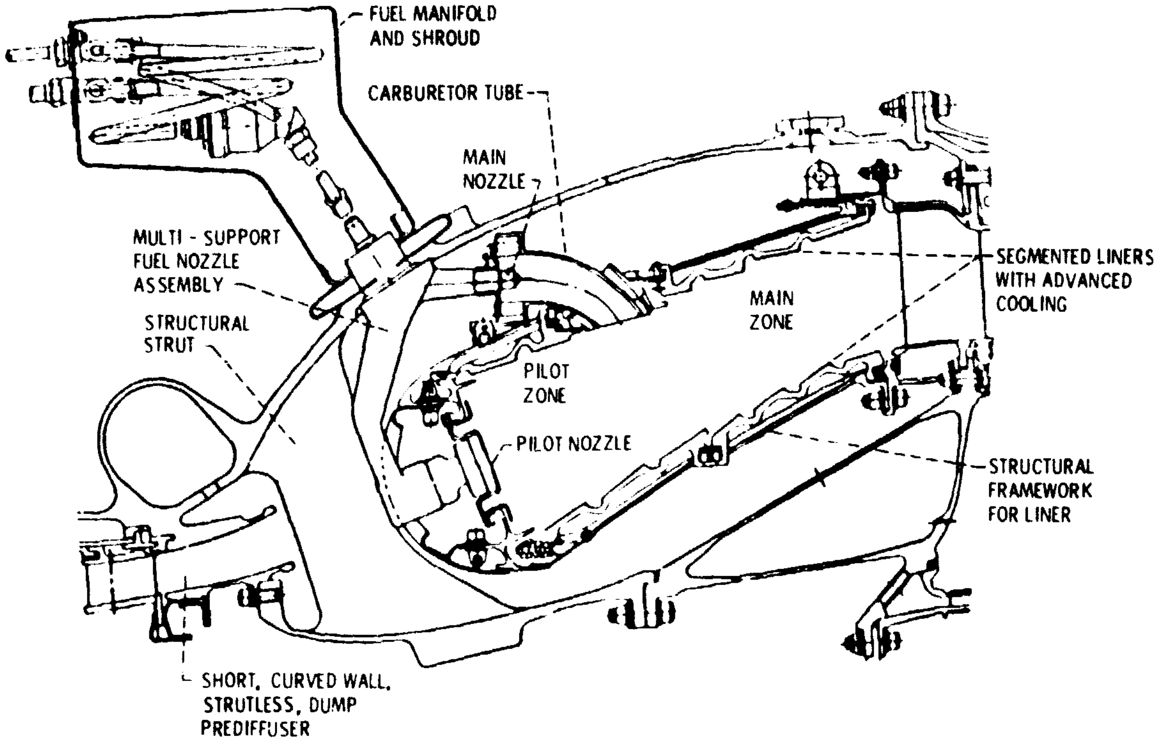


Figure 1. - Schedule of activities for the GE and P&WA Energy Efficient Engine combustor technology programs.



(a) GENERAL ELECTRIC DESIGN.

Figure 2. - Energy efficient engine combustor designs and features.



(b) PRATT AND WHITNE . AIRCRAFT DESIGN.

Figure 2. - Concluded.

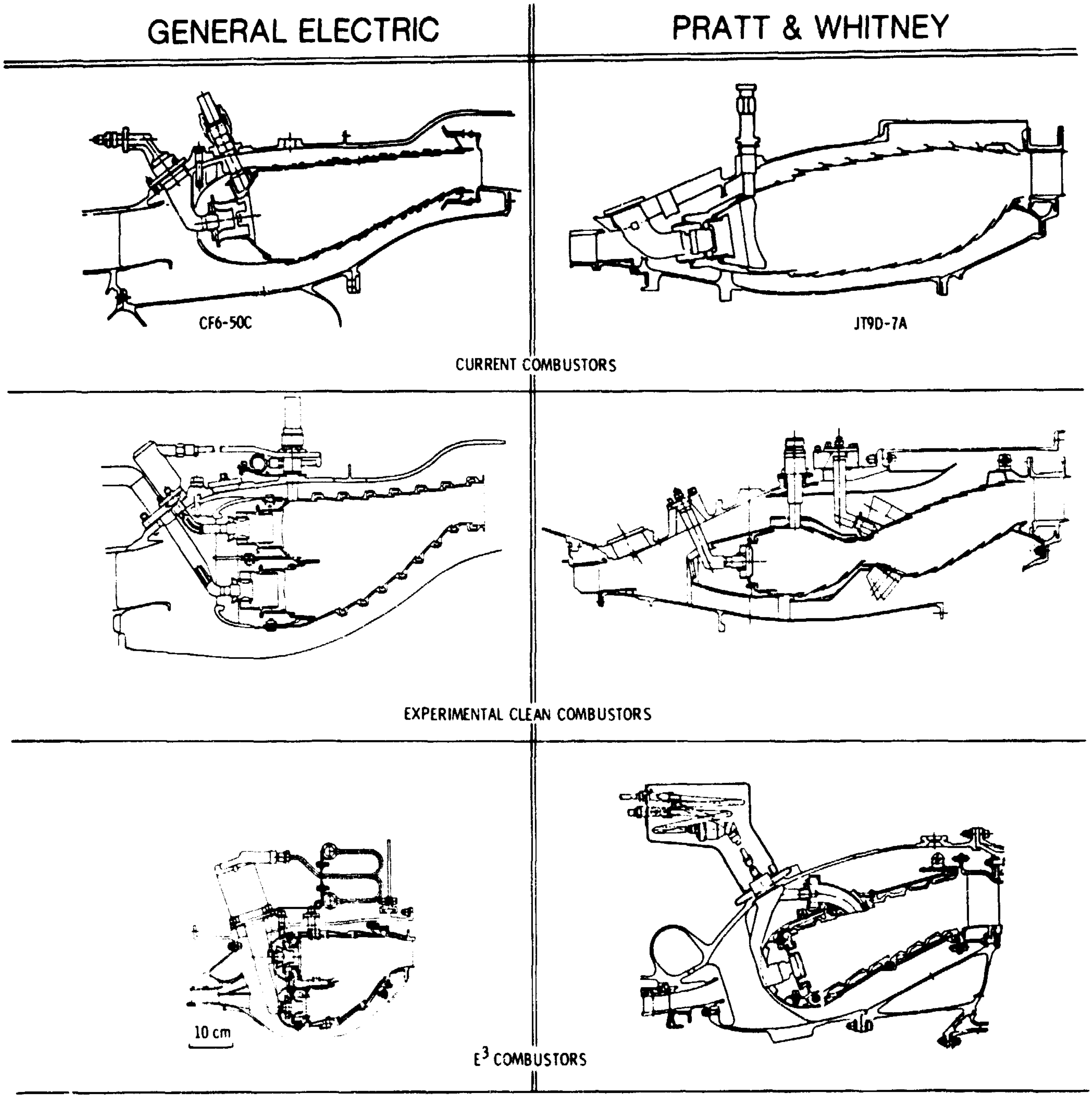


Figure 3. - Evolution of GE and P&WA high-bypass ratio engine combustors from current engines, to experimental clean combustor program designs, to energy efficient engine program designs. Engine centerlines are to the bottom of each cross section.

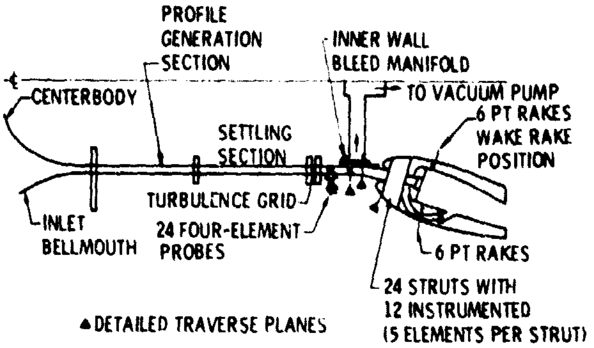


Figure 4. - P&WA diffuser/combustor model test rig schematic.

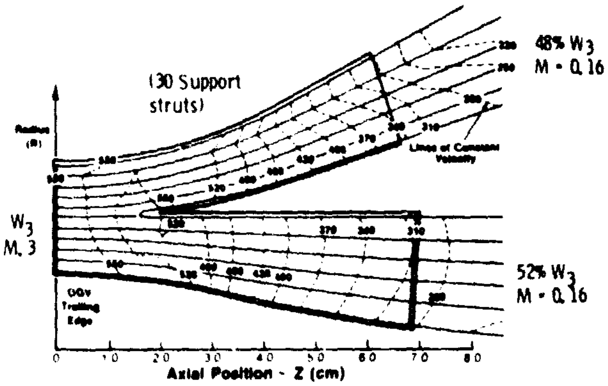


Figure 5. - GE split duct prediffuser profile and operating characteristics.

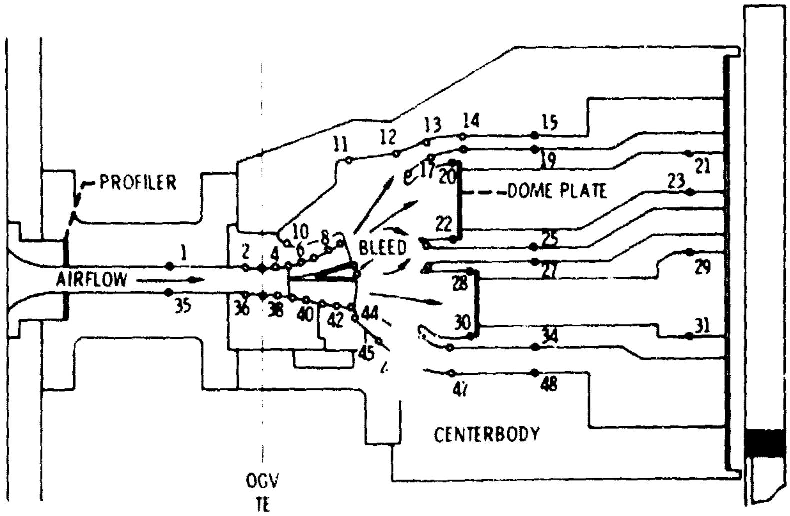


Figure 6. - GE diffuser/combustor model test rig schematic.

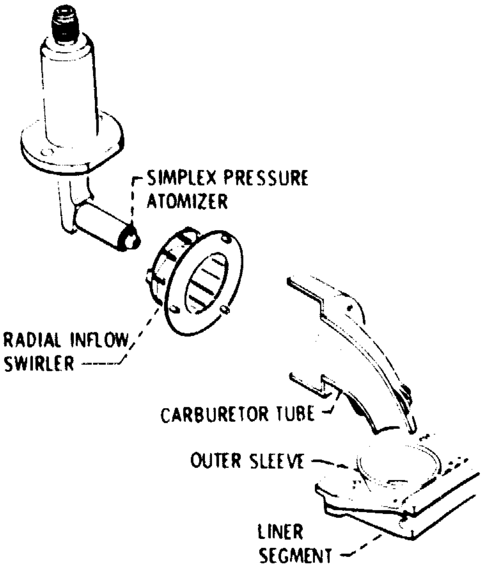
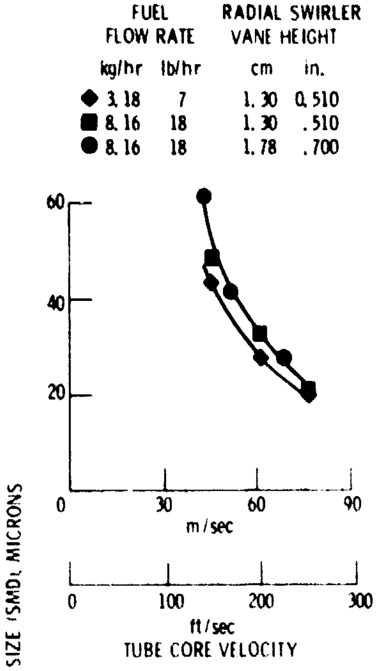
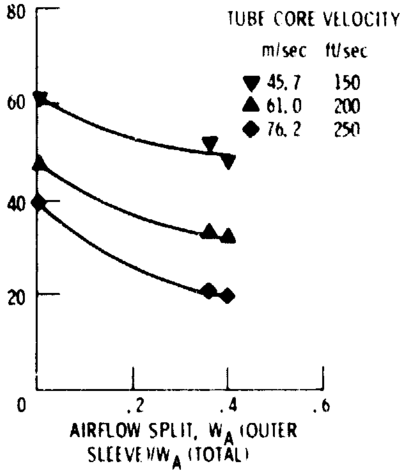


Figure 7. - P&WA E^3 combustor main zone fuel nozzle featuring carburetor tube.



(a) EFFECT OF TUBE CORE VELOCITY ON FUEL DROPLET SIZE.



(b) EFFECT OF SECONDARY (OUTER SLEEVE) AIRFLOW ON FUEL DROPLET SIZE

Figure 8. - P&WA E^3 main combustion zone fuel injector characteristics.

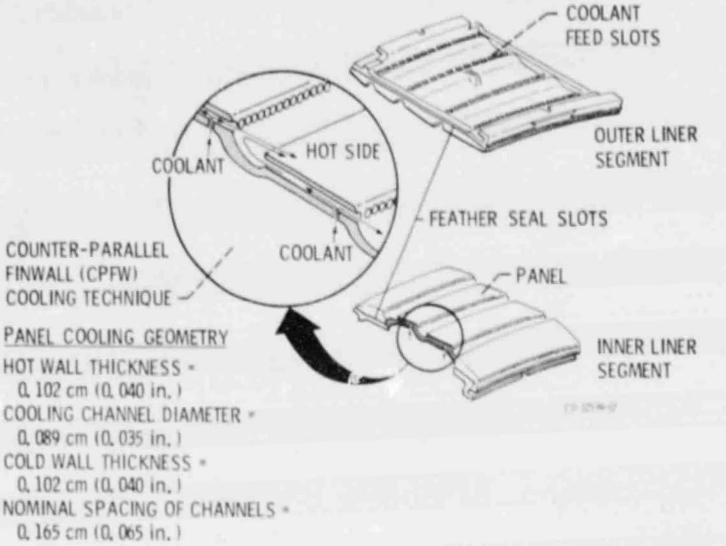


Figure 9. - Typical inner and outer liner segments with counter-parallel Finwall cooling technique illustrated for P&WA E^3 combustor.

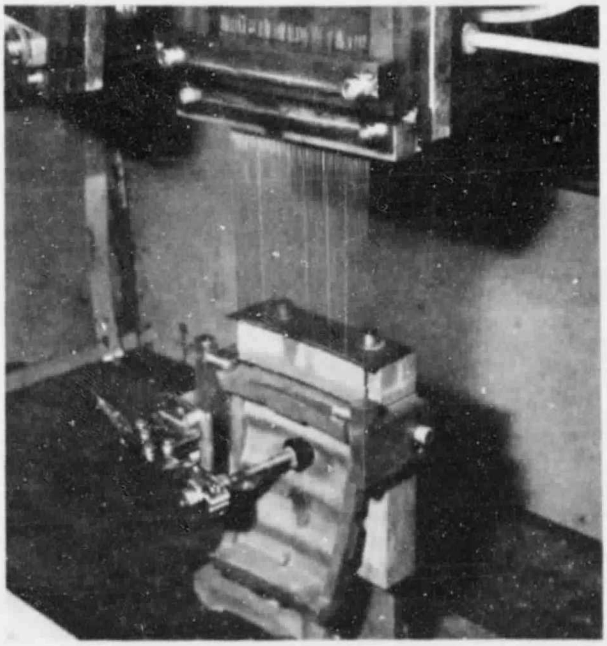
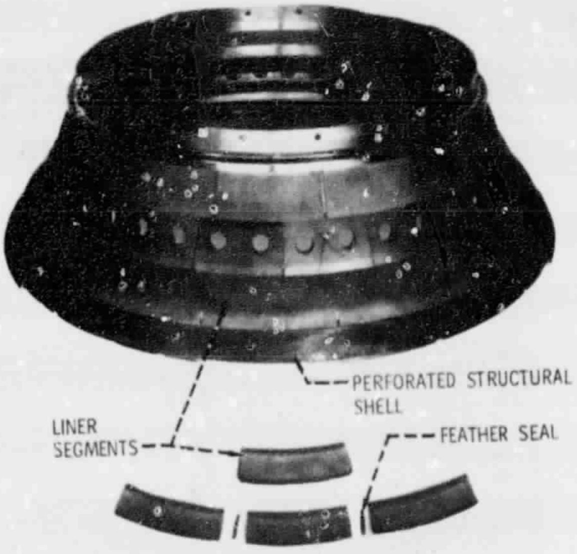
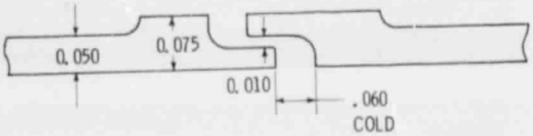


Figure 10. - Electro-chemical machining of P&WA E^3 combustor liner cooling holes.



(a) ASSEMBLY OF LINER SEGMENTS SHOWING PERFORATED STRUCTURAL SHELL. ALSO SHOWN ARE INDIVIDUAL SEGMENTS AND ASSOCIATED FEATHER SEALS AS DESIGNED IN ATEGG PROGRAM.



(b) DESIGN OF LAP JOINT REPLACEMENT FOR FEATHER SEALS AS DESIGNED IN E^3 PROGRAM.

Figure 11. - Typical inner liner, like that in GE E^3 combustor, showing segmented ("Shingle") construction.

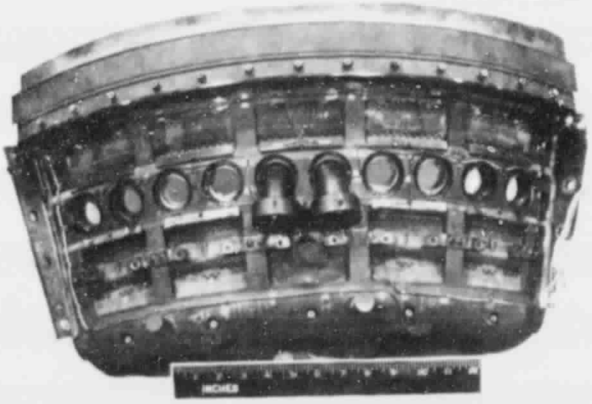


Figure 12. - P&WA E^3 90° sector combustor assembly featuring segmented liners.

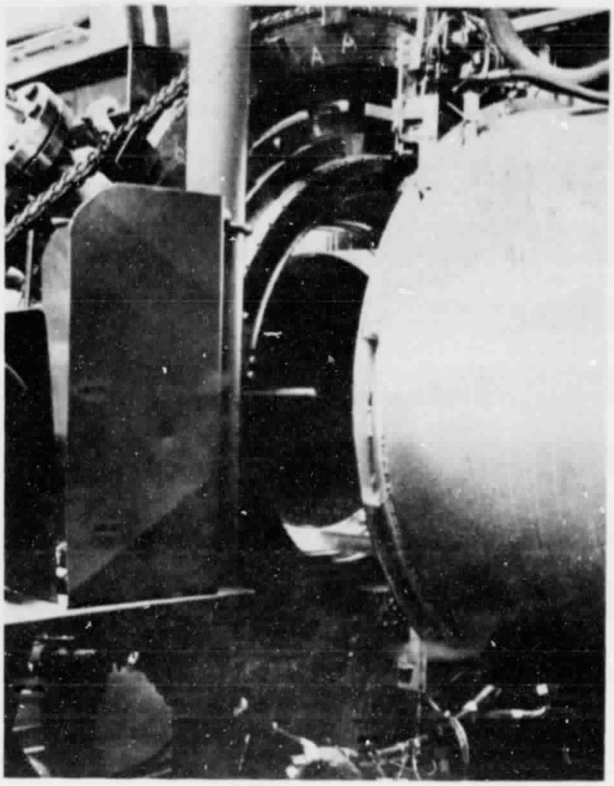


Figure 13. - GE E^3 full-annular combustor during atmospheric pressure testing.

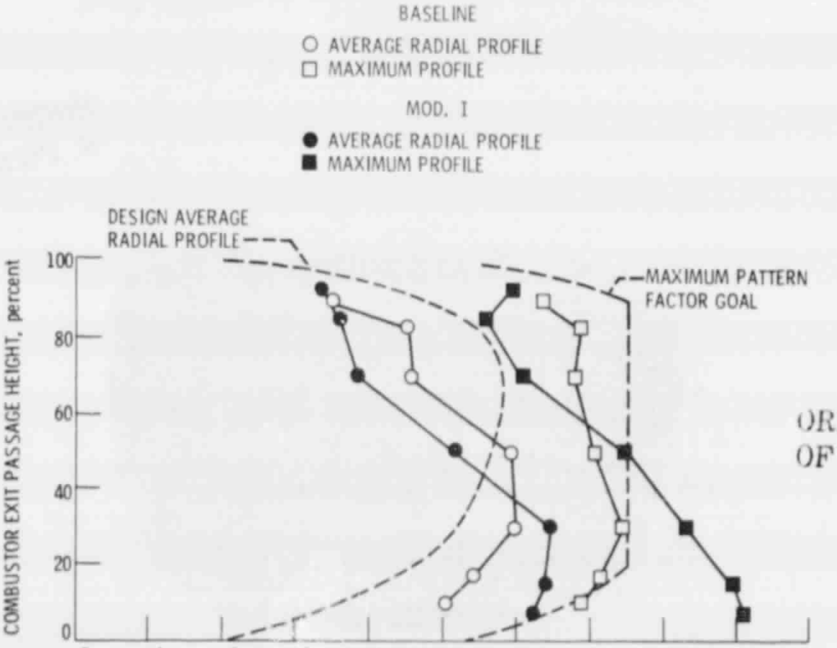


Figure 14. - Exit temperature performance of the GE E^3 full-annular combustor design having machined ring liners.