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Advanced Low Emissions Subsonic Combustor Study

Final Report

Reid Smith, et al.
United Technologies Corporation, East Hartford, Connecticut

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1.0 SUMMARY

This report presents the results of analytical studies of conceptual approaches for advanced low emissions subsonic combustors in near-term and far-term advanced engine cycles with operating pressure ratios (OPR) of 60:1 and 75:1 respectively. The study comprises Subtasks A through E of the Statement of Work for NAS3-26618, Task Order No. 7, *Advanced Low Emissions Subsonic Combustor Study*. In Subtask A, *Engine Cycle and Design Criteria*, the near-term STS1034 and the far-term STS964 cycles for an advanced ducted propulsor (ADP) engine were selected. These cycle requirements were applied to address the major effort Subtask C, *Combustion System Conceptual Designs*, which included results for Subtask B, *Barrier Technologies*. Subtask D, *Altitude Cruise Emissions Measurements*, was satisfied by a study of viable techniques being investigated by the international community. The report concludes with near- and far-term recommendations in accordance with Subtask E, *Technology Development Plans*.

The candidate comparison studies initially involved only the far-term STS964 cycle, aimed at an entry-into-service (EIS) year of 2015. Concerns became evident that this EIS year represented too advanced an engine cycle to establish a consistent progression of combustor technology development. The near-term STS1034 cycle, which has a target EIS year of 2008, was introduced later as an addendum so the development requirements could be more realistically established. Because of the late entry of the STS1034 cycle, the STS964 was the principal cycle for the study.

To begin the study, a baseline combustor configuration was defined, consistent with state-of-the-art, in-service technology of a reference Pratt & Whitney (P&W) commercial engine. The combustor from the V2500-A5/D5 engine, which is similar in size and airflow to the advanced cycles, was selected as the reference configuration. Recent certification data provided a basis for emissions estimates in scaled, advanced cycle baseline combustors at the increased pressure and temperature requirements.

Subsequent advanced combustor configurations incorporated progressively more aggressive technology, with increasing emissions reduction. A total of six concepts were assessed. Projected levels of oxides of nitrogen (NO_x) for the near-term STS1034 cycle were generally about 75 percent as high as for the far-term STS964 cycle. Both cycles indicated the same ranking order of the candidate configurations. Ranking was done on basis of projected NO_x, although carbon monoxide (CO) emissions were also estimated. Generally, CO emissions were consistently well below allowable limits in all the configurations. Emissions of total unburned hydrocarbons (THC) were assumed to follow the same trends as the CO emissions. A brief summary of pertinent configuration design features and trends of NO_x emissions results for each of the six candidate concepts, relative to the principal study cycle of the STS964 engine, follows.

The STS964 baseline combustor was of conventional, rich primary zone design. Projected emissions exhibited a cruise NO_x level about twice that of the current V2500 reference engine. The projected Environmental Protection Agency Parameter (EPAP) for NO_x was about equal to that of the current V2500 reference engine, and substantially below the current International Civil Aviation Organization (ICAO) limits. The conventional segmented FLOATWALL™ liner was found inadequate for durability. A requirement for technology advances in ceramic materials for liners with reduced cooling air was recognized.

The STS964 axially staged combustor (ASC) was scaled from the P&W ASC currently being developed in V2500 size. Two stages of combustion, both with globally lean primary zones, have been shown by development testing to yield substantial reduction of NO_x emissions. Using these data as a basis for STS964 ASC emissions projections, study results showed the STS964 ASC to reduce NO_x emissions to less than half the NO_x of the baseline conventional combustor. As in the baseline, advanced ceramics are needed for liner durability.

Conceptual designs of lean multisource combustors were assessed in an attempt to simulate the homogeneous lean fuel-air mixtures of an idealized lean premixed, prevaporized design approach, which has been shown by independent testing to produce very low NO_x emissions (about 10 percent of conventional combustor NO_x). Two concepts attempted to incorporate a multitude of realistic, small, experimental aerating fuel injectors of measured airflow capacity, but were found to require excessive bulkhead height. Two other concepts assumed injectors with improved airflow capacity. Emissions of NO_x, based on other independent test data from a small-scale lean multisource rig, were estimated to be roughly 50 percent of the ASC NO_x, but a factor of three greater than idealized lean premixed, prevaporized combustion. Assessments of producibility of these concepts indicated a clear need for the development of compact higher airflow fuel injectors. Fuel distribution manifolding was found to be extremely complex for the multisource concept, and coke prevention is considered a substantial barrier technology area.

Emissions projections for the rich-quench-lean (RQL) combustor were based on data currently being generated on a small scale combustor rig under the High Speed Research (HSR) Program. Based on that data, an RQL combustor that achieved the current High Speed Civil Transport (HSCT) goal for cruise NO_x emissions would have a cruise NO_x less than 20 percent of that projected for the baseline conventional combustor. If the rich zone can be operated at an equivalence ratio of 1.9 at the takeoff condition without producing excessive smoke, this type of combustor may be capable of operating over the entire flight envelope without having to incorporate variable geometry or a staged fuel system. Combustor final definition is dependent on the HSR Program, and on the development of advanced ceramic materials. Rich-quench-lean may not be practical for advanced subsonic applications, due to packaging requirements.

Analyses were conducted to assess the feasibility and emissions reduction potential of catalytically controlled combustion. Both rich catalytic and lean catalytic design approaches were assessed. The rich operating approach employs a pilot combustion stage that, in effect, acts as an ignition source. The catalytic reaction bed would operate at fuel-rich equivalence ratios in the range of 2.0 to 2.5 to avoid excessive temperatures. The bulk of the combustion air is mixed with the reactor products, which are oxidized in the final or main lean combustion zone. The mixer and lean zones would parallel and draw on the technology of the RQL combustor. Emissions estimates for the rich catalytic scheme were generated using a reactor network computation scheme. The estimated NO_x emissions index at cruise was less than half that of the RQL combustor, or about six percent of the baseline combustor cruise NO_x emissions index. The development problems for rich catalytic combustors are considered to be long term in difficulty. This concept was not evaluated for the near-term STS1034 cycle.

The lean catalytic combustor concept consists of a homogeneous mixer and a catalyst bed that operates at the overall lean equivalence ratio of the entire combustor. This approach has the lowest NO_x potential, with projected cruise NO_x levels one-half of the rich catalytic concept, or three percent of the baseline combustor. However, practical considerations of mixer autoignition and high-temperature material requirements for the lean-reaction at full turbine inlet temperature constitute major technology barriers for this approach. The following general conclusions apply to the various configurations:

- A current technology baseline combustor in the STS964 provides emissions that are substantially below current ICAO regulation levels.
- The use of the near-term ASC could provide about a 60 percent reduction in NO_x emissions, relative to the baseline combustor.
- While lean premixed, prevaporized combustors could offer very low NO_x emissions levels, a practical design concept has not been identified. The lean multisource approach appears to

offer some of the NO_x reduction potential of premixing, but efforts to date have produced results only slightly better than that of the ASC. Fuel system complexity and packaging for lean multisource are barrier technologies.

- Rich-burning combustor approaches — the RQL and the rich catalytic combustor — offer NO_x reduction potential that approaches or betters lean premixed, prevaporized methods, but these approaches may be constrained by combustor material considerations and packaging.

- Lean catalytic combustion may be viewed as an ultimate approach to emissions reduction but is severely constrained by catalytic substrate temperature limitations.

The results of the study of the measurement of altitude emissions reiterates the current trend of international community opinion regarding this same subject. The favored near-term approach is to measure altitude flight performance data to extrapolate ground-measured emissions to actual altitude conditions.

This study analytically investigated numerous concepts that promised potential for significant reduction in NO_x emissions in future high pressure ratio aircraft gas turbine engines that will enter revenue service after the millennium. The intent of this effort was to identify promising concepts and discover existing technological barriers to implementation, from which a development program could be structured. Two essentially separate research and development paths — rich and lean combustion — are proposed, each with its own specific barriers, but also with some common concerns. The rich path will attempt to build on the ASC, which, while globally lean, actually employs rich free-shear layer combustion. The RQL approach is probably not appropriate for the engines cycles under consideration due to packaging constraints. The lean path will endeavor to refine the lean multisource approach into an economically viable configuration. A program outline is presented to accomplish the required analysis, bench scale and sector rig testing, concept selection, and annular rig demonstration by 1999.

2.0 INTRODUCTION

Studies indicate that the evolution of gas turbine engine technology over the coming decades will lead to the capability for achieving significant further reductions in thrust specific fuel consumption. High bypass ratio advanced ducted propulsor (ADP) engines will incorporate high temperature and pressure-ratio cores to achieve these performance levels in subsonic transport aircraft. However, recent developments on the international level have served to focus renewed and expanded attention on aircraft engine emissions. Prior concerns over pollutant output in the airport vicinity have been extended to the higher altitudes where longer range climatic influences are perceived. Furthermore, the high operating temperatures and pressures of these future high-performance engines are conducive to even greater production of NO_x. The objective of this task is to conduct a study of candidate combustor concepts for future subsonic transport aircraft powerplants to identify unique technology barriers, design approaches, and development strategies for low emissions.

The scope of this study effort includes conceptual definition of the flowpath for each candidate combustor section. Compressor exit and turbine inlet elevations of the baseline ADP engine are retained. Optimally, the combustion section length of the candidate configurations should not exceed that required for the baseline conventional combustor. Outer burner case radius may be pushed outward relative to the baseline engine. Required variable geometry and/or fuel staging scheduling with power level will be identified. Airflow distributions and primary zone equivalence ratios will be specified. The physical size of critical components such as fuel injectors and swirlers will be established. Liner cooling assessments will assume the availability of ceramic matrix composite materials from the Enabling Propulsion Materials Program. Barrier technologies that must be addressed in the design of the combustion system will be defined and assessed. Emissions estimates will be made at an altitude cruise condition, and at each of the four sea-level conditions of the Environmental Protection Agency Parameter. Techniques used to estimate emissions and/or scale emissions will be specified, and the reference base will be identified. In a separate study, the development of techniques to measure altitude cruise emissions will be addressed. Each of the candidate combustors investigated will be compared and ranked relative to the baseline combustor. A recommended plan for continued technical development of selected candidate concepts will be presented.

3.0 ADVANCED CYCLES

The selection of an advanced subsonic engine cycle with an operating pressure ratio in the range of 60:1 to 75:1 as the baseline for the study was influenced by several factors. Recognizing the target pressure ratio drove the selection to a future study engine rather than a growth or derivative version of an existing engine. This ensures that the most advanced concepts and approaches can be developed without constraints of retrofit requirements. Sufficient time will be available for maturation of the technology identified in this task.

Pratt & Whitney (P&W) has conducted studies to define the technologies required to realize the potential benefits of advanced turbine engines for future subsonic aircraft. One study in particular identified large turbofan-type engines based on technologies predicted to be available in year 2010 and, hence, for entry into service (EIS) in the year 2015. The study was conducted under Task 1 of the NASA-sponsored Aeropropulsion Technology (APT) Contract (NAS3-25952) (Reference 1) and led to definition of the ultrahigh bypass ratio (UHB) ducted turbofan engine (i.e., the STS964 Advanced Ducted Propulsor [ADP] engine). A cross-sectional view of this engine is presented in Figure 3–1. This engine is selected as the reference baseline engine for the Advanced Low Emissions Subsonic Combustor Study. Targeting on this engine is consistent with the study objectives and makes available the design base of trade studies conducted under the prior contracted propulsion system study. Market research indicates that a large share of the aircraft market after the year 2000 will be for long-range subsonic widebody aircraft. These aircraft will require large high-thrust powerplants of the ADP type in thrust ranges comparable to current and projected PW4000 engine models. While the fan diameter and engine thrust rating of the STS964 ADP are approximately of PW4000 size, the airflow and geometric size of the core burner more closely approximate the smaller V2500 current engine size.

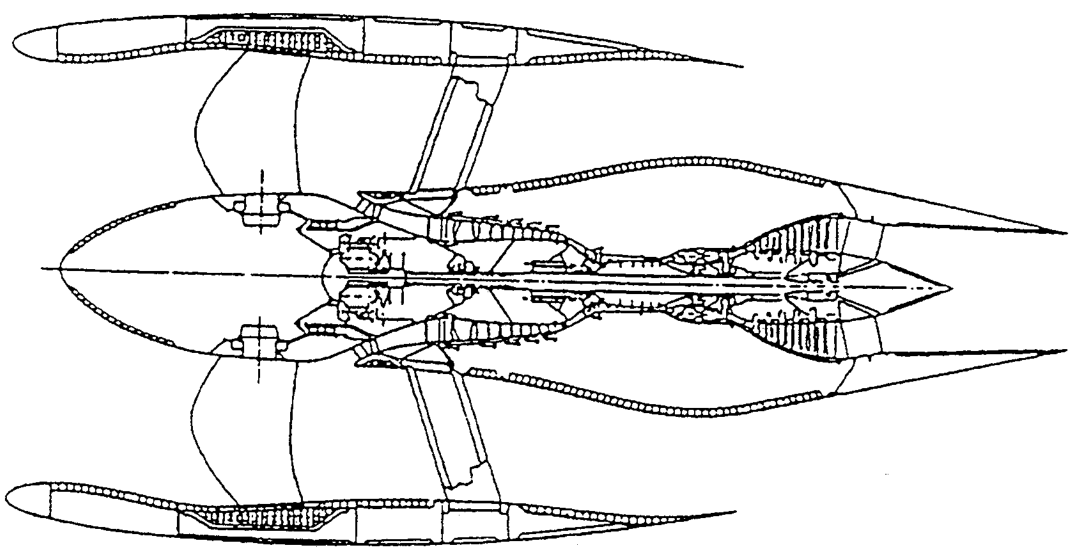


Figure 3–1. STS964 Advanced Ducted Propulsor Engine

Table 3–1 lists pertinent operating parameters at takeoff and cruise of the STS964 ADP engine and for comparison purposes, those of current technology PW4000 and V2500 turbofan engines. Relative to the PW4000, the STS964 incorporates progressively more advanced material assumptions, enhanced component efficiencies and more advanced design concepts. The availability of materials paces the evolution of the engine and allows higher temperatures in the last stages of the compressor which accommodates higher core pressure ratios. The 250°F increase in maximum compressor discharge temperature (T_3) in the STS964 relative to the current technology PW4000 is associated with a near doubling of the core pressure ratio. Improved turbine materials and cooling technology also permit progressively higher allowable turbine inlet temperatures and increased specific work output. Gear drive availability and enhanced low spool performance lead engines toward substantially higher bypass ratios which produce significant improvements in the thrust specific fuel consumption. Since the thrust size is essentially the same as the PW4000, the higher bypass ratio leads to substantially lower core airflow sizes, with the combustor inlet airflow parameter being about one-fourth that of the PW4000.

Table 3–1. Design and Operating Parameters for Future Subsonic Engines

	V2500	*PW4000*	*STS1034*	*STS964*
Type	Turbofan	Turbofan	ADP	ADP
EIS	Current	Current	2008	2015
Rated OPR	33	35	60	75
Bypass Ratio	5	5	20	25
Rated Thrust (lb)	30,000	60,000	61,800	61,800
Takeoff				
P_{t3} (psia)	481	471	638.1	876.2
T_{t3} (°F)	1078	1055	1202	1314
T_{t4} (°F)	2650	2380	2950	3200
W_{ab} (lb/sec)	112.2	254	113.9	97.7
F/A	0.0268	0.0220	0.0310	0.0344
Flow Parameter	9.15	21.0	7.28	4.69
Cruise				
P_{t3} (psia)	155	146	248.1	300.2
T_{t3} (°F)	831	795	1021	1086
T_{t4} (°F)	2115	1810	2688	2946
W_{ab} (lb/sec)	40.31	88.6	46.4	34.9
F/A	0.0204	0.0159	0.0287	0.0328
Flow Parameter	9.34	21.5	7.20	4.57

As task efforts of emissions estimates for the STS964 cycle progressed toward sufficient definition to characterize the trends and narrow the focus of the study, there was concern that the STS964 engine, with a projected EIS date of 2015, represented too advanced an engine cycle to establish a consistent progression of combustor technology development. By conducting parallel combustor assessments in a more near-term, but still aggressively-defined engine, the development requirements could be more realistically established. This process led to definition of the STS1034 engine, also a gear-driven ADP with a nominal bypass ratio of 20:1 and overall pressure ratio of 60:1. This engine is based on technology that is projected to be available for EIS in the year 2008.

Table 3–1 includes the pertinent operating parameters at takeoff and cruise for the STS1034 cycle compared to the STS964 and current engines. The STS1034 data was originally generated for a V2500-size core, for which the STS1034 thrust would have been 70650 pounds at takeoff, with a burner airflow of 130.2 lb/sec. By scaling the airflow down to 113.9 lb/sec, the thrust is scaled down to 61,800 lb at takeoff to compare with the STS964 cycle. The core engine size of the STS1034 is also reduced to be slightly smaller than the V2500. No other performance parameters are affected by this change. The table indicates that while the STS1034 combustor temperature and pressure environments are, by design, moderated somewhat from those of the STS964, they still represent aggressive operating levels. Additional performance parameters for the STS1034 and STS964 cycles are tabulated on Table 3–2. These list the four sea-level operating conditions stipulated for airport vicinity regulations by the Environmental Protection Agency Parameter (EPAP) and at altitude cruise. The table shows that both the advanced cycles show a relatively narrow fuel-air ratio range from idle to takeoff. The high idle fuel-air ratio occurs because of the energy demands on the relatively small core to drive the large fan and the gearbox. Furthermore, the bypass ratio at idle increases by factors of 2 to 3 relative to takeoff, which is unique to advanced ADP engine performance characteristics and adds to the idle fuel requirement. As a result, conventional turbofan engine fuel-air turndown ratios, currently in the 35 to 40 percent range, become about 65 percent in the advanced ADP cycles. This aspect is a unique characteristic of ADP engines, and has significant impacts on combustor design because of reduced operational constraints and requirements on fuel staging and variable geometry systems.

Table 3–2. Summary of Engine Operating Conditions for Emissions

		Idle	*Approach*	*Climb*	*Takeoff*	*Cruise*
STS 1034						
	Altitude (ft)	0	0	0	0	35K
	Flight Mach No.	0	0	0	0	0.86
	2008 EIS					
	Percent Thrust	7	30	85	100	N/A
	60 OPR					
	P_{t3} (psia)	60.8	194.5	536.4	638.1	248.1
	20 BPR					
	T_{t3} (R)	888	1223	1594	1662	1481
	T_{t4} (R)	2191	2646	3263	3410	3148
	Fuel/Air Ratio	0.0200	0.0231	0.0292	0.0310	0.0287
	Waburner (lb/sec)	13.20	39.75	98.1	113.91	46.40
	Fn (lb)	4325	18531	52528	61800	9506
	TSFC	0.2200	0.1780	0.1960	0.2060	0.5038
	Bypass Ratio	35.7	24.7	20.9	19.4	22.0
STS 964						
	Altitude (ft)	0	0	0	0	35K
	Flight Mach No.	0	0	0	0	0.86
	2015 EIS					

Table 3–2. (Continued) Summary of Engine Operating Conditions for Emissions

	Idle	*Approach*	*Climb*	*Takeoff*	*Cruise*
Percent Thrust	7	30	85	100	N/A
75 OPR					
P_{t3} (psia)	73.9	250.4	578.8	876.2	300.2
25 BPR					
T_{t3} (R)	974	1374	1590	1774	1546
T_{t4} (R)	2395	2938	3332	3660	3406
Fuel/Air Ratio	0.0222	0.0262	0.0306	0.0344	0.0328
Waburner (lb/sec)	10.05	31.47	68.05	97.7	34.9
Fn (lb)	4325	18540	43260	61800	8250
TSFC	0.186	0.160	0.173	0.196	0.500
Bypass Ratio	63	41	29	25	30

Another aspect of the ADP cycles which has beneficial impact is the relatively low thrust specific fuel consumption (TSFC) of the high bypass engines. Table 3–2 lists the TSFC for the STS964 and STS1034. These values are about 55 percent of typical TSFC levels in conventional current turbofan engines. This results in a beneficial reduction of the EPAP coefficients (kg fuel burned per kN rated thrust) in the ADP engines relative to current engines. Values of EPAP coefficients for the STS1034 and STS964 engines are listed in Table 3–3. The actual coefficients are typically one-third to one-half of those for conventional engines. This has the effect of reducing airport vicinity oxides of nitrogen (NO_x) EPAP emissions relative to current engines, even though the emissions indices at the advanced pressures and temperatures are substantially greater than in current engines.

Table 3–3. EPAP Coefficients (kg/kN)

	STS1034	*STS964*
Idle (7 Percent)	0.6796	0.5748
Approach (30 Percent)	0.3634	0.3270
Climb (85 Percent)	0.6237	0.4541
SLTO (100 Percent)	0.2447	0.2332

The combined effects on NO_x emissions from the overall pressure ratio (OPR) parameter and the bypass ratio (BPR) parameter in the ADP cycles relative to current engines is indicated by the graph shown on Figure 3–2. In the reference V2500 engine, the OPR is about 30, and the BPR is about 5. As the OPR increases in the advanced cycles, the resulting higher pressures and temperatures cause the NO_x emissions to increase. The advanced cycle increase in BPR are associated with the improved specific fuel consumption inherent to the ADP engines, and cause corresponding decreases in the NO_x EPAP value.

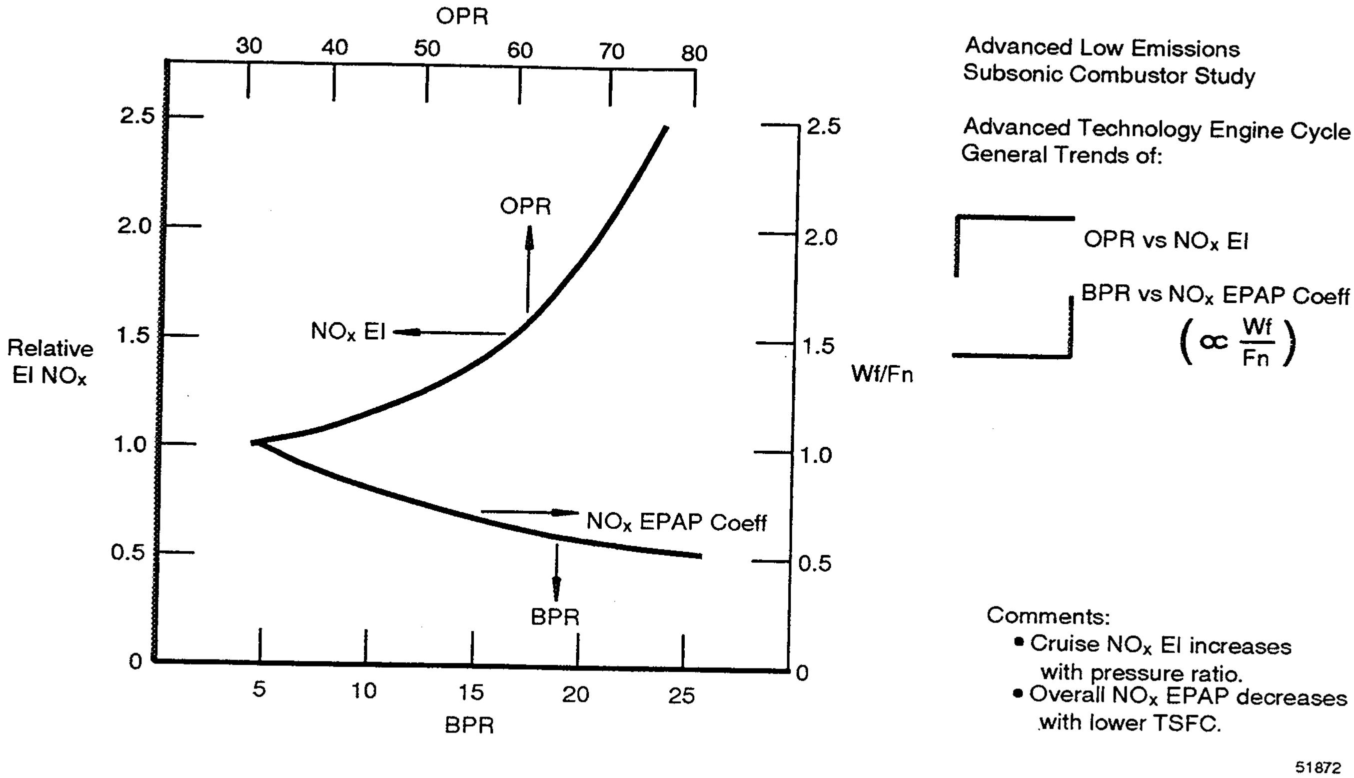


Figure 3–2. Engine Cycle Effects on NO_x

4.0 COMBUSTOR SYSTEMS

The study procedure discussion encompasses combustor definitions for the two scaled combustors and the four conceptual combustors, all emissions estimating procedures, advanced ceramic liner considerations, and smoke concerns. Because of the late entry date of STS1034 performance into the study, some of the discussion is presented only for the STS964. In those instances, the assumption is that the application to the STS1034 would be similar and easier.

4.1 SCALED COMBUSTORS: DEFINITION AND GEOMETRIC SIZING

Combustor definition is initiated by establishing a baseline or reference configuration consistent with state-of-the-art, in-service operation. Subsequent configurations would incorporate progressively more aggressive technology, with increasing emissions reduction potential to provide the basis for a benefit assessment. The combustor from the V2500-A5/D5 engine was selected as the reference configuration. This combustor is representative of state-of-the-art, in-service technology in Pratt & Whitney (P&W) commercial engines and incorporates single-stage, rich primary zone combustion with fuel introduced by a single pipe aerating injector. The liner incorporates segmented FLOATWALL™ construction. The V2500 combustor was selected over other current engine configurations (such as the PW2000 and PW4000) because the geometric size and airflow are consistent with the STS964 and STS1034 combustors. Recently available certification data from the V2500-A5/D5 model were also available to provide a basis for emissions estimates.

4.1.1 Conventional Baseline Combustors

Conventional scaling is accomplished primarily by comparing the compressor discharge/diffuser inlet (Station 3) flow parameters ($W_3 \frac{\sqrt{T_3}}{P_3}$) for the STS964 and the reference V2500 engines. Assuming that diffuser inlet Mach number is to be maintained, an area scaling factor may then be determined. This area scaling factor is then applied locally to the effective flow areas (AC_d) of the reference engine's combustor liner components (i.e., fuel injector swirlers, combustion/dilution holes, and liner coolant areas). This results in like airflow distributions in both scaled advanced ducted propulsor (ADP) and reference V2500 combustors. This is advantageous in that it preserves the stoichiometry of the reference combustor, thereby enhancing the reliability of emissions scaling. In the case of the STS964 baseline combustor, it was ultimately deemed desirable to redirect cooling air saved from the advanced ceramic liners (to be discussed in Section 4.4) to add 4 percent combustor airflow to the primary zone of the combustor as a precaution for smoke control. The extra primary zone air did not detract from the confidence in forthcoming emissions scaling because there is a V2500 database of emissions measurements which quantify the effect of an added 4 percent primary zone air.

The primary zone combustion airflow in the V2500 reference combustor and in the STS1034 baseline combustor is 19 percent of combustor airflow, of which 7 percent enters through the injector air swirler. The STS964 baseline combustor has 11 percent swirler air and the primary zone combustion has 23 percent. These percentages are noted on the sketches of Figure 4–1, which shows cross-sectional views of the V2500 reference combustor and the STS964 baseline combustor. The STS1034 baseline combustor would be of a size somewhere between the two. The primary zone equivalence ratio for each of these three combustors is plotted versus overall fuel-air ratio (f/a) from idle to takeoff power on Figure 4–2. The fuel-rich burning with a transition to an eventual fuel-lean combustor exit condition is representative of current P&W emissions technology, and needs to be improved. However, the fuel-rich primary zone approach does offer the virtues of extremely stable combustion, which manifests itself as excellent lean blowout performance.

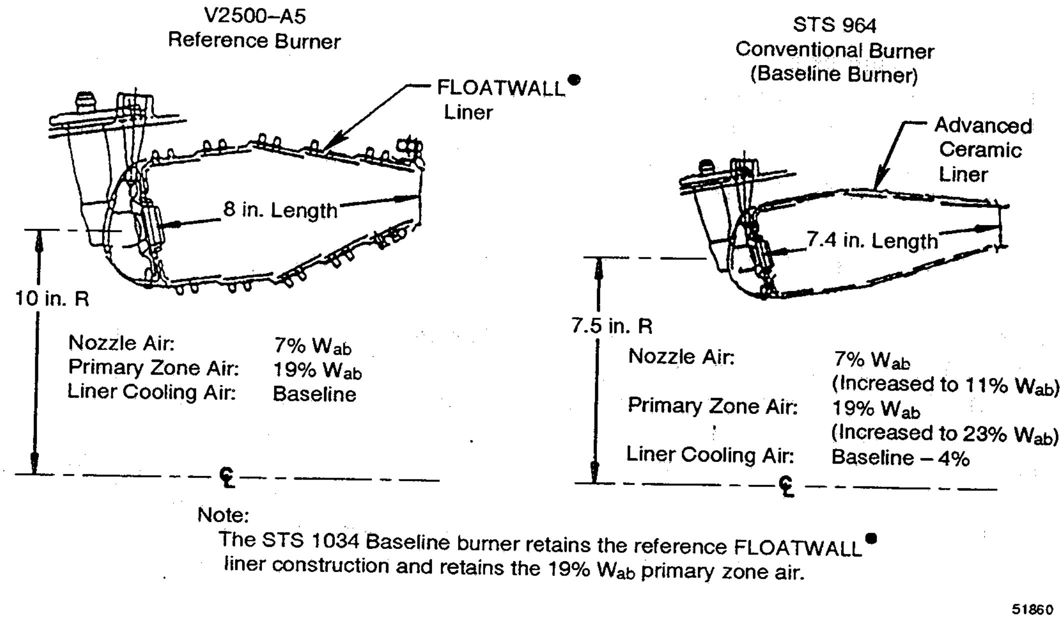


Figure 4–1. Comparisons of Burner Sizes — Conventional Burners

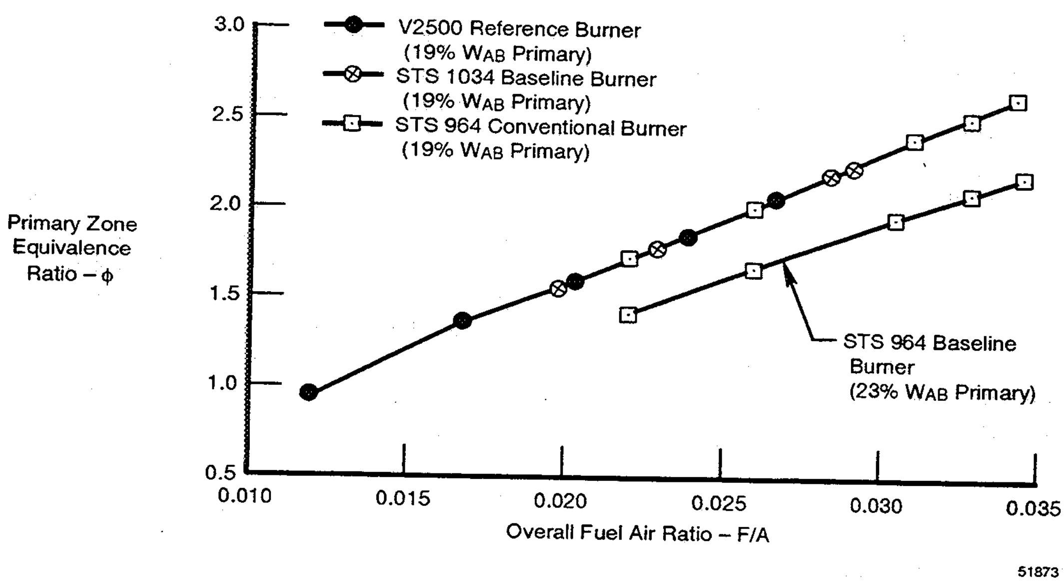
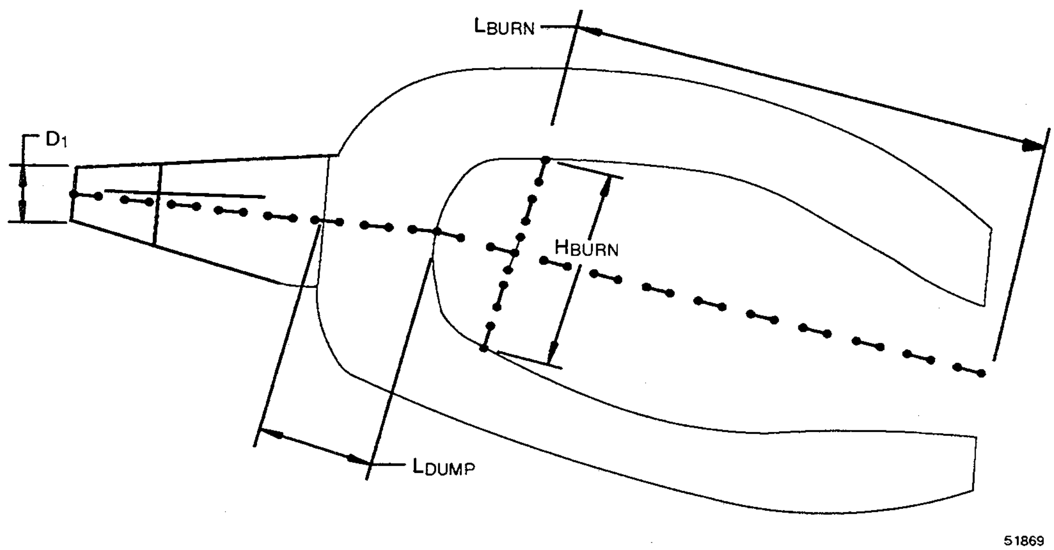


Figure 4–2. Conventional Burners — Primary Zone Equivalence Ratio Versus Overall Fuel/Air Ratio

The geometric scaling of the fuel injector is of interest because of manufacturability considerations in the smaller size. The area scaling factor dictates the new swirler diameter, and the remainder of the injector is scaled according to established proprietary design rules for the pertinent dimensional parameters within the injector. When done, the scaled STS964 injector was evaluated for producibility concerns and found to be marginally acceptable. The STS1034 injector would be sized somewhere between the reference injector and the STS964.

In addition to the foregoing major combustor definition parameters, there are several other scaling parameters of generic interest in combustor design that should be evaluated to ensure reasonable compliance with reference levels. The pertinent parameters are tabulated in Figure 4–3 for the V2500 and the STS964 conventional combustors. The volumetric heat release rate (VHRR, defined by Equation 1) in the STS964 conventional combustor is slightly higher than the typical commercial engine value represented by the V2500 baseline combustor, but is acceptable. The cold flow residence time (defined by Equation 2) for the STS964 is comfortably within the satisfactory range of about 7 to 9 milliseconds. The combustor-length to dome-height ratio is slightly high in the STS964; shortening the combustor and increasing the height may be desirable. The distance L_{DUMP} is required to provide sufficient length to install and remove the fuel injectors, and the ratio L_{DUMP}/D_1 (D_1 being the diffuser inlet height) should be between 2 and 4 to provide optimum diffuser dump pressure recovery. These relationships appear satisfactory.



$$VHRR = \frac{W_f \frac{lb}{hr} \ x\ 18,500 \frac{Btu}{lb}}{(Vol) ft^3 \ P_{T3} Atm} = Volumetric\ Heat\ Release\ Rate \left(\frac{Btu}{Hr \cdot ft^3 \cdot Atm} \right)$$

$$T_{RES} = \frac{(Vol) ft^3 \rho \frac{lb}{ft^3}}{W_{AB} \frac{lb}{sec}} = Cold\ Flow\ Residence\ Time\ (sec)$$

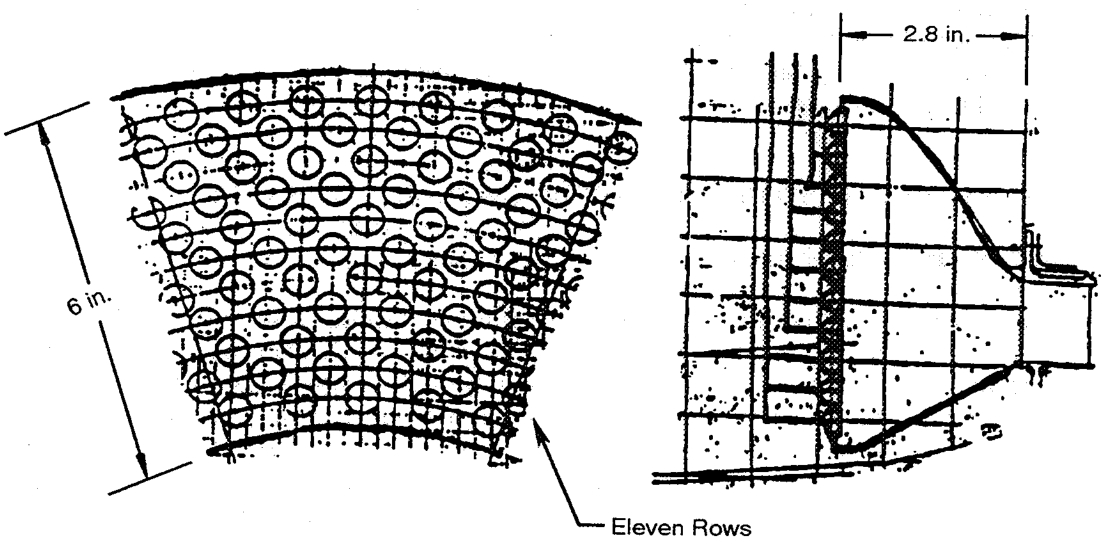
Parameter	*V2500 Reference Burner*	*STS964 Conventional Burner*
VHRR	5.7 x 10^6	6.3 x 10^6
Cold T_{RES}	8.1 x 10^{-3}	8.0 x 10^{-3}
L_{Burn}/H_{Burn}	2.24	2.5

Figure 4–3. Generic Burner Sizing Parameters (Continued . . .)

reduction relative to current technology. However, NO_x emissions are about three times higher than the idealized premixed, prevaporized data.

$$Hot\ \tau_{RES} = \frac{(Vol)\ ft^3}{W_{AB\ lb_s/sec}} \left[\frac{P_{B\ lb_s/ft^2}}{(53.3\ ft/^\circ R) T_4\ ^\circ R} \right] \qquad \text{Equation 3}$$

Several attempts were made to devise an acceptable configuration of a lean multisource combustor for the STS964. These attempts were not successful. Currently available fuel injectors cannot meet the airflow requirements and still be packaged in a reasonably-sized bulkhead, and fuel manifolding requirements present technology barriers of untenable magnitude. Two representative conceptual designs for the lean multisource approach are shown in Figures 4–5 and 4–6. The former uses current technology fuel injectors, and the latter assumes major injector improvements to restore the bulkhead to a reasonable size. Specific design considerations addressed for establishing the number of injectors, bulkhead height requirements, and fuel manifolding in the lean multisource approach are discussed in the following subsections.



Comments:

- Residence time 2 milliseconds
- 673 injectors, 0.5 in. dia 0.030 sq in. ACd
- Excessive bulkhead height
- Abnormal flowpath
- Fuel distribution concerns

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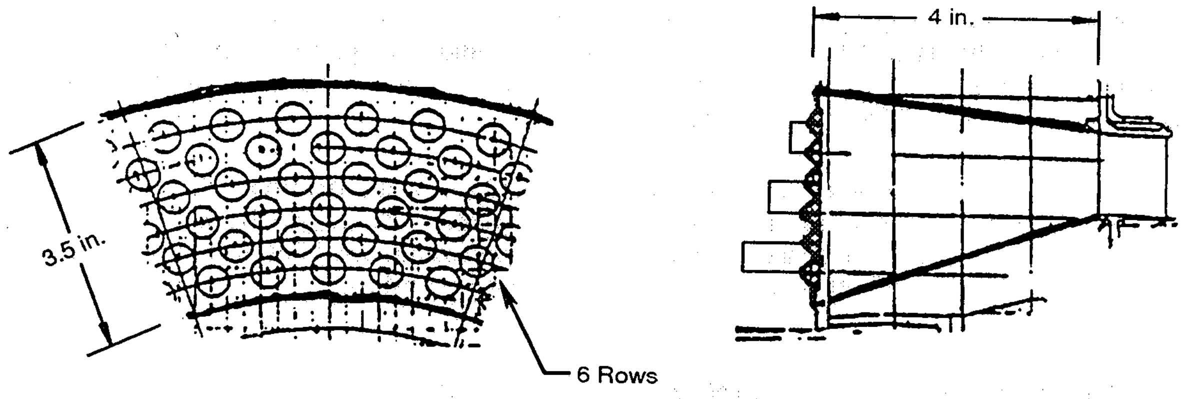
Figure 4–5. STS964 Enhanced Lean Burning Configured With Currently Available Injectors



Comments:
- Residence time 2 milliseconds
- 336 injectors, 0.5 in. dia 0.060 sq in. ACd
- Reasonable bulkhead height, flowpath
- Fuel distribution still a concern

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Figure 4–6. STS964 Enhanced Lean Burning Configured With Injectors Not Yet Invented

4.2.1.1 Number of Injectors and Bulkhead/Combustor Geometry

In constructing the flowpaths for the two STS964 lean multisource conceptual combustors, the required volume to achieve a residence time of 2 milliseconds was first determined. This, in conjunction with a bulkhead height, would provide a combustor length. The bulkhead configuration was addressed by examining the airflow capacity of two small, currently available, experimental aerating fuel injectors in reasonably spaced patterns. The smaller of the experimental injectors has an outer diameter of 0.5 in. and an effective airflow area of 0.03 in^2. The diameter of the other injector was 0.938 in., with an effective flow area 0.065 in^2. The number of these injectors needed to pass 87.5 percent of combustor airflow (12.5 percent was assumed for cooling an advanced ceramic liner), a standard formulation relating airflow, effective flow area, and pressure drop was applied (Equation 4). The resulting numbers were 673 of the 0.5-in. diameter configuration and 310 of the 0.938-in. diameter configuration. These quantities cannot be realistically packaged. Bulkhead height would be 12 to 14 inches, more than double the available space. The 673 injector configuration shown on Figure 4–5 demonstrates the dilemma of designing this approach. The volume required to attain a hot residence time of 2 milliseconds, together with the extreme bulkhead height, results in a combustor with unacceptably steep liner walls.

$$\frac{(W_{A\ All\ Nozzles})\sqrt{T_3}}{P_{Hood}\times N_{Nozzles}\times 0.9(AC_{D1\ Nozzle})} = \sqrt{\frac{2g}{R}}\sqrt{\frac{P_{Hood}-P_B}{P_{Hood}}} \qquad \text{Equation 4}$$

To alleviate the bulkhead concerns of the preceding two multisource combustors, hypothetical injectors of twice the airflow capacity of the previous 0.5-in. diameter injectors were assumed. Such injectors would require extensive development, but are considered fabricable. The resulting 336 injector configuration, Figure 4–6, shows that the bulkhead height is reasonable, and the combustor length required for a hot residence time of 2 milliseconds exhibits reasonable proportions.

The lean multisource sketch of Figure 4–6 applies to the STS964 conditions only. The corresponding injector and bulkhead packaging for the less severe STS1034 conditions have not as yet been addressed. However, because the basic STS1034 combustor scales to about 50 percent more combustor airflow area relative to the STS964, the assumption is that 50 percent more injectors (a total of 504) could be packaged into the larger STS1034 bulkhead.

The lean primary multisource concept is highly dependent on the development of compact, high-airflow fuel injectors. This result indicates a clear need for technology advancements to produce combustor air-fuel introduction concepts that produce homogeneous mixtures in a mechanically more compact envelope (i.e., one with a higher airflow to frontal area ratio).

4.2.1.2 Fuel Manifolding and Operability Requirements

Fuel manifolding for multisource bulkheads is generally conceived of as small diameter tubes each making a full circumferential ring around the outside of the bulkhead at incremental radii of bulkhead height. Each ring would feed a circumferential group of injectors, and the rings would be supplied by radial tubes which penetrate the diffuser case and receive fuel from an exterior control valve system. Figure 4–7 shows a schematic of a fuel manifold arrangement devised for the 673 injector configuration previously shown. The complexity of the circumferential rings is substantial, and airflow blockage is a major concern. External plumbing complexity is also a considerable concern.

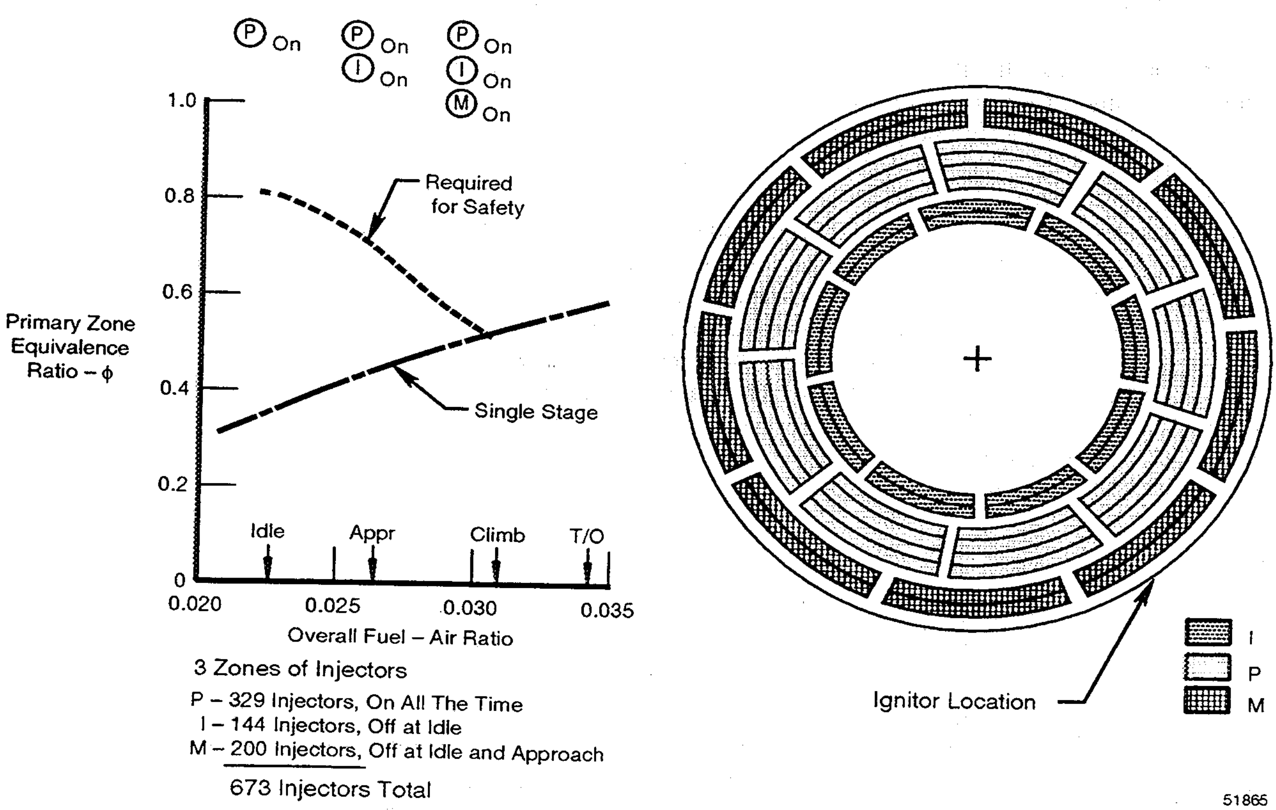


Figure 4–7. STS964 Enhanced Lean Burning Staging Requirements

Fuel staging requirements arise from the examination of the lean primary zone equivalence ratios created by the 87.5-percent combustor airflow distribution. This level of airflow produces a lean equivalence ratio at high power levels for minimum NO_x production. However, at idle power, the 87.5-percent swirler air would create a primary zone equivalence ratio too low for adequate combustion stability. The graph in Figure 4–7 shows a plot of primary zone equivalence ratio versus power setting for the STS964 multisource combustor. To achieve the desired equivalence ratios, all the injectors are operational at high power levels, such as takeoff, cruise, and climb. With further power reductions, successive clusters of injectors are shut off, until at idle approximately 47 percent remain operational. This results in a redistribution of fuel to fueled injectors to maintain adequate fuel-air ratio for stability purposes. The airflow through the swirlers of the unfueled injectors is assumed to no longer participate in the primary zone combustion. However, practical experience has indicated that inefficient combustion is likely to occur on the boundaries between fueled and unfueled regions. A tabulation of the number of injectors that would be active at various stages of performance is included in Figure 4–7.

A fuel manifolding schematic for the 336 hypothetical injector combustor is shown on Figure 4–8. This demonstrates the reduction of fuel manifolding complexities that could be realized with the development of improved injectors. While somewhat less complex, a substantial number of manifold rings are still required. A tabulation of the number of injectors that would be active at various stages of performance is included on Figure 4–8. In manifold schematics, the injectors to be turned off at lower power levels were positioned at either the innermost or the outermost radius of the bulkhead to preserve the combustion zone in the center bulkhead region. In addition, the manifolding systems all preserve several injectors along the outer bulkhead radius to be always active, enhancing combustor relight capability.

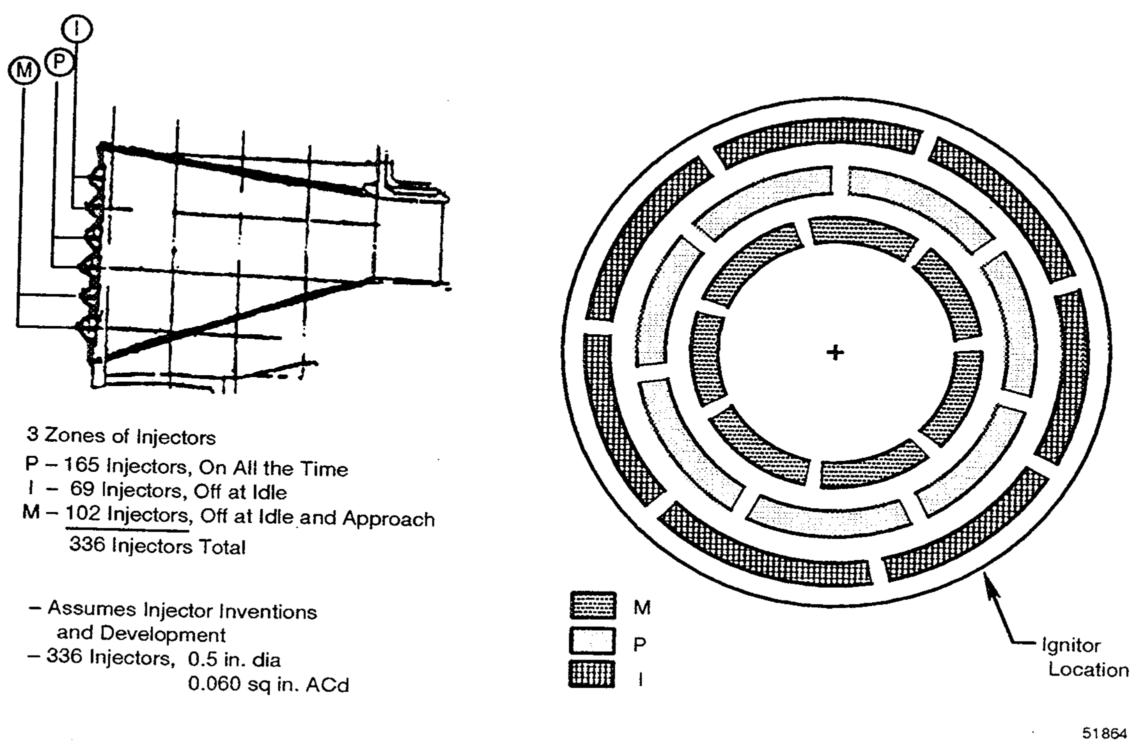


Figure 4–8. STS964 Enhanced Lean Burning Manifolding With Injectors Not Yet Invented

The required tube inner diameter of each of the radial feed manifold lines and each of the circumferential manifold lines was calculated for assumed fuel velocities of 10 to 40 ft/sec. Typical inner diameters range from 0.06 to 0.20 in., which seems reasonable. However, note that these are inside diameters. Additional space must be allocated for thermal insulation. Pratt & Whitney practice is to maintain adequate fuel velocity in manifolding to minimize heat pickup, but this may create higher pressure losses in the many sharp bends and branches of the small-diameter tubes. Even at acceptable velocities, the fuel flowrate in each injector at any power setting is extremely low, and coking seems inevitable.

The design of a fuel distribution system capable of providing coke-free operation with the multisource injection and the thermal environment of either the STS964 or the STS1034 engine is considered a substantial technology barrier. A more complete design study to define the practical limits of a lean multisource system in terms of coking, pressure loss, combustor case strength (many injector penetrations), and reliability is required.

4.2.2 Rich-Quench-Lean Combustors

The rich-quench-lean (RQL) combustor, which is currently being developed in the High Speed Research (HSR) program for the High Speed Civil Transport (HSCT), is included in the subsonic combustor concept evaluation subtask. The RQL concept is summarized in Figure 4–9, which shows a 15-degree segment containing one swirler and fuel injector. The RQL combustor incorporates a fuel-rich primary zone, a quench zone of reduced cross-sectional area for rapid mixing of the rich primary zone effluent with cross-jet dilution air at high throughflow gas velocity, and a lean-burn zone for completing the combustion process. The intent is to achieve low NO_x by a series of three processes, each of which is beneficial to low NO_x production. Initial combustion occurs at a high fuel-rich stoichiometry to achieve low flame temperature in a well-mixed primary zone, which achieves homogeneity by improved injector spray patterns and by avoidance of conventional wall coolant ingestion. All primary zone air is introduced through the swirlers and injectors in the bulkhead.

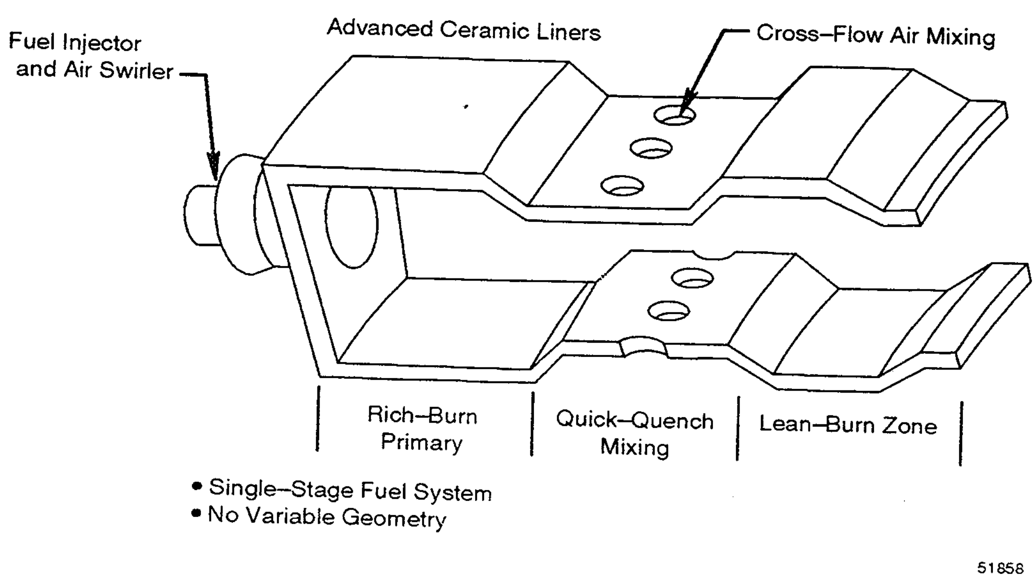


Figure 4–9. Rich-Quench-Lean Combustor — 15° Segment

The quick-quench to a lean mixture is accomplished by intense cross-jet mixing in the reduced cross-section area of the combustor. This minimizes the residence time of the burning gases at the undesirable stoichiometric equivalence ratio, and allows a low-Btu gas formed in the rich zone to complete combustion in a lean-burn low-temperature environment downstream of the quench.

The liner walls of the RQL combustor are advanced ceramic materials currently being developed in the Enabling Propulsion Materials (EPM) Program for monolithic ceramics and ceramic matrix composites (CMCs).

Development data from the HSR program indicates a rich primary zone equivalence ratio of 1.9 is achievable with good homogeneity and combustion stability. Aerothermal definition studies indicate that if the rich zone can be operated at an equivalence ratio of 1.9 without encountering excessive smoke, this type of combustor should be capable of operating over the entire flight envelope without having to incorporate variable geometry or a staged fuel system. However, packaging and size requirements will dictate the applicability of RQL. The HSR program should be employed to experimentally define the RQL potential for ADP type cycles.

4.2.3 Rich Catalytic Combustors

In general, catalytic combustor concepts are still in the conceptual stages of hardware definition, and thus are depicted as schematic sketches. The rich catalytic combustor of Figure 4–10 incorporates a torch-ignitor pilot, a mixer and catalytic reactor bed, a quick-quench rapid mixer, and a lean-burning zone to complete combustion.

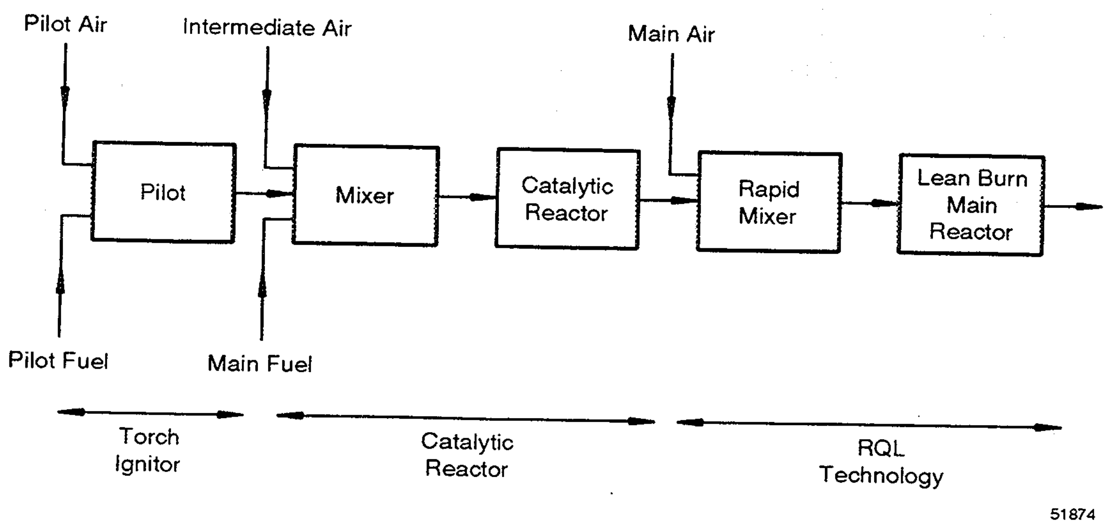


Figure 4–10. Rich Catalytic Combustors — Simple System; No Fuel Staging or V.G.

The torch-ignitor pilot is required at engine starting to achieve a mixture inlet temperature to the catalytic reactor bed greater than 1350K (2430°R). The torch-ignitor pilot is then left on over the full flight cycle to ensure adequate catalyst bed inlet temperatures. The ignitor operates at a constant fuel flowrate, set by starting considerations, and falls to a f/a of 0.0063 at takeoff power. The torch ignitor is sized for idle combustion efficiency greater than 99.5 percent. Stability and coking are not problems.

In the mixer downstream of the pilot, main fuel is not on at start, but comes on during the spool-up to idle power. A fuel distribution valve will have a special ramping characteristic to bring on main fuel at sub-idle speed after engine start: above idle, normal engine fuel demand with power will be followed. Coking of main injectors should not be a problem since they are flowing at all normal engine operating conditions. However, due to variation of torch-ignitor exit temperature with power, autoignition is a concern. Autoignition delay is approximately constant for all power levels at about 1.3 milliseconds, which is extremely short in comparison with typical mixing times: thus, a two-stage device will be necessary. Torch-ignitor products will be mixed with air first to lower the temperature before main fuel injection into the mixed gases. Sizing of the first part will be scaled from the mixer development work of the RQL mixer technology, and the second part will be based on autoignition limits. On a bulk basis, if autoignition occurs, it should not damage the catalyst bed by overtemperature because there will be insufficient air for complete combustion. Less-than-perfect mixing is only a concern in terms of smoke.

The catalytic reactor shown schematically on Figure 4–10 is a catalyst bed of zirconia material with a maximum temperature limit taken as 1950K (3510°R). Considerations of high-temperature operation and a long service life dictate the use of rare-earth type catalysts. The beds would be a graded cell approach to optimize catalytic reaction requirements with low-loss pressure drop across the head. Figure 4–11 shows generic graphs of reacting gas temperature versus a range of bed equivalence ratios, applicable to the idle and takeoff power points of the STS964 ADP engine cycle. At a practical design limit of 1800K (3240°R) for the catalyst bed, the fuel-rich catalytic reactor should be designed for equivalence ratios above 2 at low power and above 2.5 at high power. Table 4–1 shows a tabulation of the design overall equivalence ratio in each stage of the rich catalytic combustor over the full range of STS964 flight conditions. The distribution of equivalence ratios produces a device that is a *Lean-Rich-Lean* combustor. These equivalence ratios satisfy the desired low-temperature fuel-rich catalytic reactions for low NO_x, while simultaneously preserving the previously-noted catalyst bed temperature requirements for lightoff, combustion efficiency, and durability. Corresponding gas temperatures at each reactor component are presented on Table 4–2, and it is seen that the bed temperature limits are satisfied. The reacted fuel-flow splits at each stage are tabulated on Table 4–3. This table shows that the desired low-NO_x criterion (burning as much fuel as possible in the catalyst bed) would be accomplished with about one-third of the fuel being burned in the catalyst at all high-power conditions. The sizing of the catalytic reactor was very roughly estimated based on 60 ft/sec reference velocity and previous experience. The resulting overall length of the complete combustor arranged in series is a serious concern for packaging in the engine.

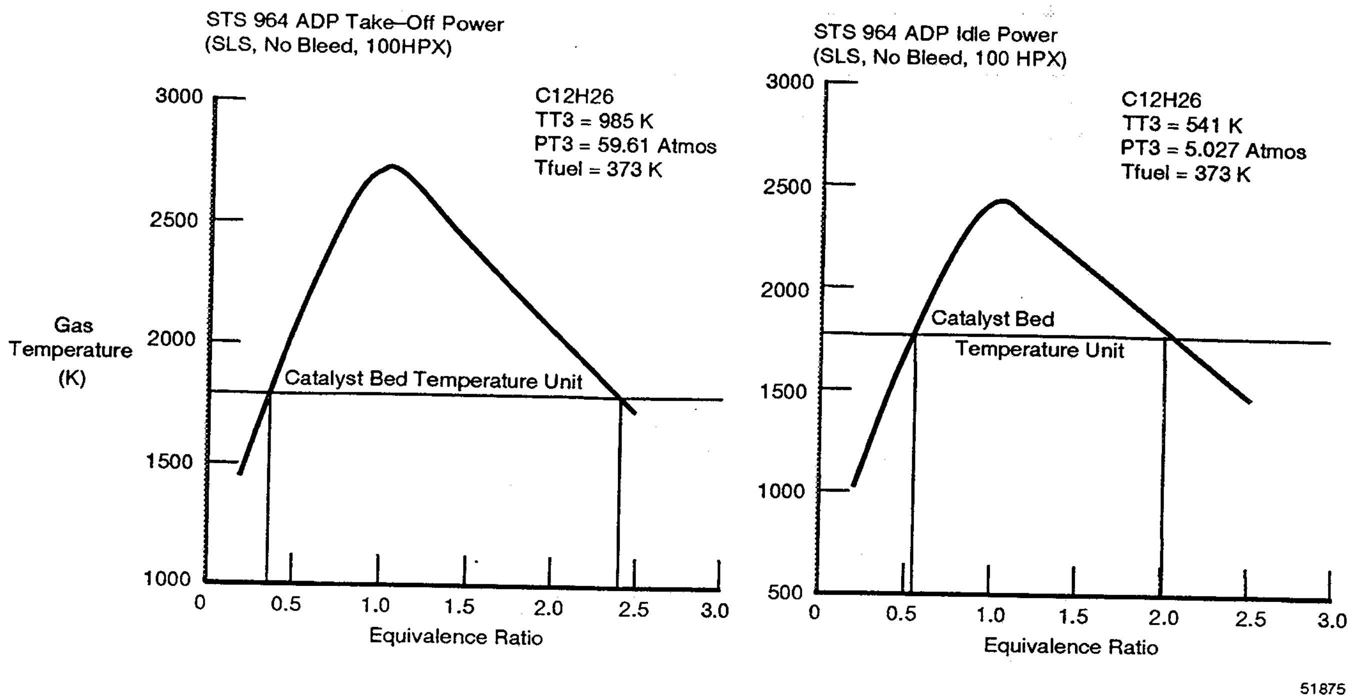


Figure 4–11. Rich Catalytic Combustor — Catalytic Bed Temperatures

Table 4–1. Rich Catalytic Combustor Equivalence Ratio Summary

Condition	Pilot	Mixer	Cat. React.	Rapid Mix.	LBMR
S.L. Idle	0.90	1.78	1.78	0.32	0.32
Approach	0.28	2.09	2.09	0.38	0.38
Climb	0.13	2.45	2.45	0.45	0.45
Takeoff	0.09	2.75	2.75	0.50	0.50
Cruise (nominal)	0.25	2.62	2.62	0.48	0.48
Idle Descent					

Table 4–2. Rich Catalytic Combustor Inlet/Outlet Temperatures in °K

Conditions	Pilot	Catalyst Bed	Main Ractor
S.L. Idle	541/2350	1520/1950	825/1330
Approach	763/1443	1167/1863	988/1645
Climb	883/1206	1019/1715	1056/1867
Takeoff	985/1209	1031/1597	1114/2048
Cruise (nominal)	858/1464	1176/1596	1012/1892

Table 4–3. Rich Catalytic Combustor Reacted Fuel Splits (Percent)

Conditions	Torch Igniter	Catalyst Bed	Lean Main Reactor
S.L. Idle	37.3	17.9	44.7
Approach	10.1	36.7	53.1
Climb	4.0	36.1	59.8
Takeoff	2.4	33.2	64.2
Cruise (nominal)	7.2	30.1	62.5

The rapid mixer and lean burn main reactor components of the rich catalytic combustor will be designed consistent with criteria that come directly from RQL combustor development in the HSR and HSCT programs. These segments are functionally identical to their quick-quench lean-burn counterparts in the RQL combustor. The lean-burning zone is aided in low NO_x production by the partially reacted state of the entering gases, which constitute a low-Btu fuel.

The simple in-line configuration shown in Figure 4–10 has a second disadvantage in addition to its excessive length. This additional disadvantage is the generation of smoke within the catalyst bed when it is operated with equivalence ratios in the range of 1.7 to 2.8. Although pure catalytic reaction can promote oxidation of long-chain hydrocarbons and soot precursors, catalytically-supported combustion requires much higher equivalence ratios, in the range of 6.0 to 10.0, to effectively minimize smoke production.

Enriching the catalytic reactor in the in-line configuration would be accomplished at the expense of reducing the intermediate air introduced into the fuel/air mixture upstream of the catalyst bed. As discussed, one of the functions of this intermediate air is to lower the temperature of the gases exiting the torch ignitor pilot, reducing the risk of autoignition in the mixer and the subsequent damage to the catalytic reactor. Ignition delay times in the mixer are already estimated to be marginal with the current quantity of intermediate air. Therefore, reducing the intermediate air to raise the catalytic reactor equivalence ratio and decrease smoke is not a feasible option for the in-line configuration.

A parallel arrangement (Figure 4–12) of the pilot combustor and catalytic reactor would allow a suitable increase in the catalyst bed equivalence ratio in order to reduce smoke, without increasing the risk of autoignition. For low NO_x emissions, the goal is to catalytically react as much of the fuel as possible. With the parallel arrangement, the catalytic reactor would be unfueled at engine start and idle power levels, with the combustion process occurring in the pilot, mixer, and lean burn main reactor sections. At higher power levels, the catalytic reactor processes the bulk of the total fuel flow, serving as a low heating value gas generator for the conventional, lean-burn main reactor. The parallel arrangement would have an inherently higher integrated NO_x value (EPAP) relative to the in-line configuration, due to the increased idle-power contribution from the pilot conditions.

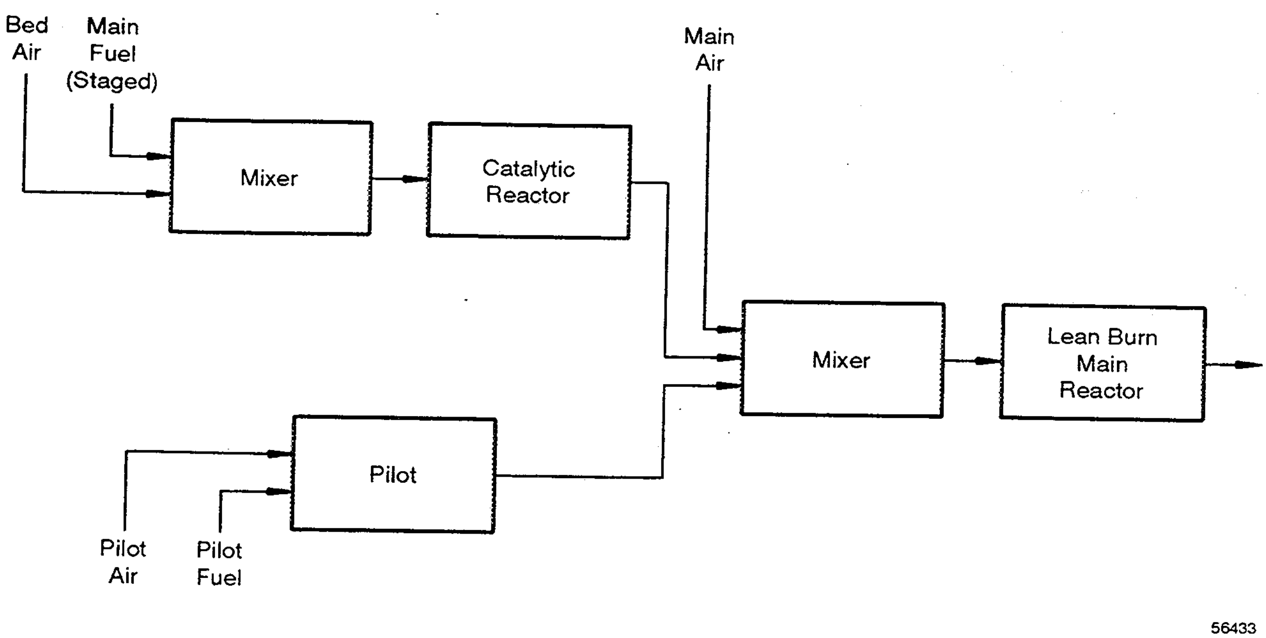


Figure 4–12. Parallel Hybrid Catalytic Combustor

Like all staged combustion systems, the catalytic reactor must be fueled, ignited, and up to operating temperature at a power level below that of flight approach. This is an engine safety requirement, since thrust delays or gaps are not acceptable in the event of a missed landing and go-around attempt. The approach power condition for the STS964 cycle gives an air inlet temperature to the combustion section of 763K (1374°R), with a pressure of 17.03 atmospheres. The catalytic reactor would have to achieve light-off at operating conditions somewhat reduced from these (i.e., at a lower power level). Furthermore, it would have to achieve very high combustion efficiencies at these conditions.

Potential catalytic reactor bed materials include noble metal catalysts, which have a relatively high reactivity and have demonstrated lightoff with fuel/air inlet temperatures in the range of 400–500K, the lower limit being for JP4 fuel (Reference 24). Transition metal oxides have achieved lightoff with bed inlet temperatures greater than 640K, while rare-earth catalysts require inlet temperatures around 600K for ignition, with some sensitivity being shown to fuel type and condition at introduction. Aging of the catalyst has been shown to exert an adverse influence by increasing the minimum ignition temperature, although aging tests typically are run for 1000 hours (Reference 25). An engine is expected to operate on the wing for considerably longer — several thousand hours. Use of noble metal catalysts as starters might be feasible, although concerns remain about their high vapor pressure and long-term reactivity. It appears that bed temperatures of 600–650K or greater could be anticipated as necessary for ignition.

It is not sufficient for the catalytic reactor to simply achieve ignition; it must also exhibit a combustion efficiency high enough to prevent both thrust-loss at approach as well as the generation of excessive carbon monoxide and hydrocarbon emissions in the lean burn main reactor. Blazowski and Walsh (Reference 26) and Anderson, et al. (Reference 27), have shown for JP4 and propane fuels that catalytic reactor combustion efficiency is relatively insensitive to pressure at these levels, and that to achieve high combustion efficiencies, the reactor bed inlet temperature must exceed 650°K with an outlet temperature of 1350°K.

It is difficult to satisfy these efficiency criteria with an over-rich reactor at approach power without diverting more fuel than is desirable to the pilot burner. This results in an increased NOx contribution from the pilot. For example, at the approach condition, the maximum equivalence ratio allowable in the catalytic reactor to maintain the 1350K exit temperature is 2.96. If the catalytic reactor equivalence ratio at take-off is selected as 7.5, then, at approach power, only 50 percent of the total engine flow is reacted catalytically. The equivalence ratio for the lean burn main reactor is 0.4, which may induce stability problems, even with the preheating effect of the pilot. The catalytic reactor equivalence ratio of 2.96 is in the smoke-producing range; and the main reactor temperatures would be too low for significant carbon burn-up to occur. The size of the pilot combustor would also increase, as would the fuel system and control complexities since continuous modulation of the pilot fuel flow becomes necessary.

Given these considerations, it appears that, at least for the study cycle STS964, the parallel arrangement of the rich catalytic combustor would have severe difficulties meeting aircraft operation safety requirements, and would forfeit a large portion of its low emissions potential.

4.2.4 Lean Catalytic Combustors

The lean catalytic combustor is comprised of the simple array of components shown in the schematic drawing of Figure 4–13. All the combustor airflow and all of the fuel are mixed homogeneously. The catalytic reactor operates at a lean equivalence ratio set by the overall f/a, and discharges directly into the turbine. This system is considered to be the ideal catalytically-supported combustion system, offering the greatest potential for low emissions. However, there are major development obstacles to be overcome.

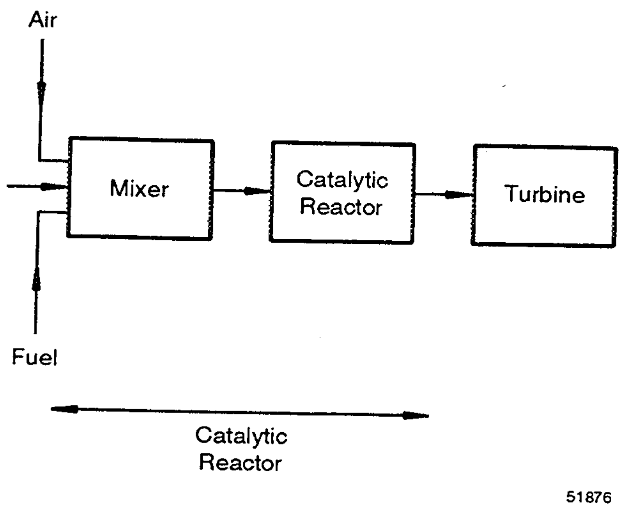


Figure 4–13. STS964 Lean Catalytic

A homogeneous mixture is critical for the success of lean catalytic combustion. The autoignition delay time of 1.3 milliseconds precludes premixing, so mixer technology requires substantial development.

The catalyst bed material must withstand temperatures equal to full combustor exit temperature (3410°R at takeoff). This requirement is in excess of the practical design limit of 3240°R assumed for the zirconia bed of the rich catalytic reactor, and is in substantial excess of limits for conventional containment materials required to house the catalyst bed. Lean catalyst bed materials technology requires substantial development.

The ignition temperature of aged rare-earth type catalysts is of the order of 1350K (2430°R). This temperature is far above the compressor discharge temperature at sea-level idle. Therefore, a lean catalytic system is not self-starting. It is not viewed as a practical system.

4.3 EMISSIONS ESTIMATING PROCEDURES

The primary focus in estimating emissions was NO_x; secondary attention was directed at CO. Emissions of total hydrocarbons (THC) were assumed proportional to CO. Smoke was considered, but primarily in a qualitative sense. Levels of emissions were expressed in terms of emission index (EI), whose units are grams of pollutant per kilogram of fuel burned (g/kg). The primary figure of merit for evaluating emissions is currently the Environmental Protection Agency Parameter (EPAP), which attempts to quantify emissions in terms of a landing/takeoff (LTO) cycle intended to simulate aircraft operation in the vicinity of an airport. This cycle comprises four operating modes and associated durations: takeoff (100 percent rated static thrust) for 0.7 minutes, climb (85 percent thrust) for 2.2 minutes, approach (30 percent) for 4 minutes, and taxi/idle (7 percent) for 26 minutes. The total mass of pollutants emitted by an engine during this cycle are individually summed and normalized by the engine 100 percent thrust level to produce the characteristic number called the EPAP. Units of the EPAP are grams of pollutant per kilonewton of thrust (g/kN). In this study, EPAP values were calculated for NO_x and CO. The NO_x emissions were further characterized by estimating a nominal cruise EI. Equations 5 through 11 define the pertinent relationships of the terminology for emissions assessment.

- EPAP Coefficient at Performance Condition *i*:

$$(EPAP\ Coefficient)_i\ \frac{kg}{KN} = \frac{(W_F)_i \times (Time\ at\ i)}{KN\ Rated\ Thrust} \qquad \text{Equation 5}$$

where:

(Time at Idle) = 26.0 Minutes	(7 Percent rated thrust)
(Time at Approach) = 4.0 Minutes	(30 Percent rated thrust)
(Time at Climb) = 2.2 Minutes	(85 Percent rated thrust)
(Time at Takeoff) = 0.7 Minute	(100 Percent rated thrust)

- Environmental Protection Agency Parameter (EPAP)

$$EPAP\left(\frac{g}{KN}\right) = \sum_i (EPAP\ Coefficient)_i \times EI_i \qquad \text{Equation 6}$$

where

$$EI = \frac{Grams\ Pollutant}{Killograms\ Fuel}$$

$$EI_{NO_X} = \frac{g\ NO_X}{kg\ Fuel};\ EI_{CO} = \frac{g\ CO}{kg\ Fuel};\ EI_{THC} = \frac{g_{THC}}{kg_{FUEL}} \qquad \text{Equation 7}$$

- Current limits on maximum allowable emissions x (1–engine factor)

$$EPAP\ NO_X = [40.0 + 2(OPR)]\frac{g}{KN} \times (0.862) \qquad \text{Equation 8}$$

$$EPAP\ CO = [118.0]\frac{g}{KN} \times (0.814) \qquad \text{Equation 9}$$

$$EPAP\ THC = [19.6]\frac{g}{KN} \times (0.649) \qquad \text{Equation 10}$$

$$Smoke\ No. = 83.6\,(KN\ Rated\ Thrust)^{-0.274} \times (0.776) \qquad \text{Equation 11}$$

4.3.1 Emissions Estimating Procedures for Scaled Combustors

For both the conventional combustor and the axially staged compressor (ASC), NO_x was assumed to be a function of pressure, temperature, and humidity according to the formulation of Equation 12. However, the assumed pressure dependency is simplistic and is only applicable to a first-order estimate for conventional P&W combustors. At the time of the study, pressure dependency for the ASC was not well known, but subsequent testing has demonstrated that it is a function of injector/combustor configuration and equivalence ratio. The assumption of inverse square root behavior for the ASC is useful from a qualitative viewpoint, as the proper trends are predicted by this assumption. The CO emissions were assumed to vary inversely with pressure according to Equation 13.

$$EI\,NO_X \sim P_B^N \, e^{aT3} \, e^{-bH} \qquad \text{Equation 12}$$

Where:

$N = 0.5$
$a = 0.0024$ for T_3° R
$b = 0.0188$ for H g/kg
$b = 18.8$ for H lb/lb

and

$$H_{STD} = 0.0063 \frac{lb\ H_2O}{lb\ Dry\ Air} \ or\ H_{STD} = \frac{g\ H_2O}{kg\ Dry\ Air}$$

$$EI\,CO \sim P_3^{-1.0} \qquad \text{Equation 13}$$

For the STS964 and STS1034 conventional combustors, NO_x and CO emissions were scaled directly from the recently acquired V2500-A5/D5 engine emissions certification data set. Scaling with Equations 12 and 13 used fuel-air ratio as the common parameter linking these data to the STS964 and STS1034. Temperature and pressure versus overall fuel-air ratio for all engines is shown on Figure 4–14. Figure 4–15 shows the NO_x EI values measured in the V2500 reference combustor and scaled to the STS964 and STS1034 cycles. For cruise NO_x EI, the humidity correction factor from Equation 12 was applied. Figure 4–16 shows the CO EI values measured in the V2500 reference combustor and scaled to the STS964 and STS1034 cycles. For the ASC, scaling of NO_x and CO emissions was performed by the same procedure as for the conventional combustor, except the basis data was annular rig emissions data measured for a prototype ASC.

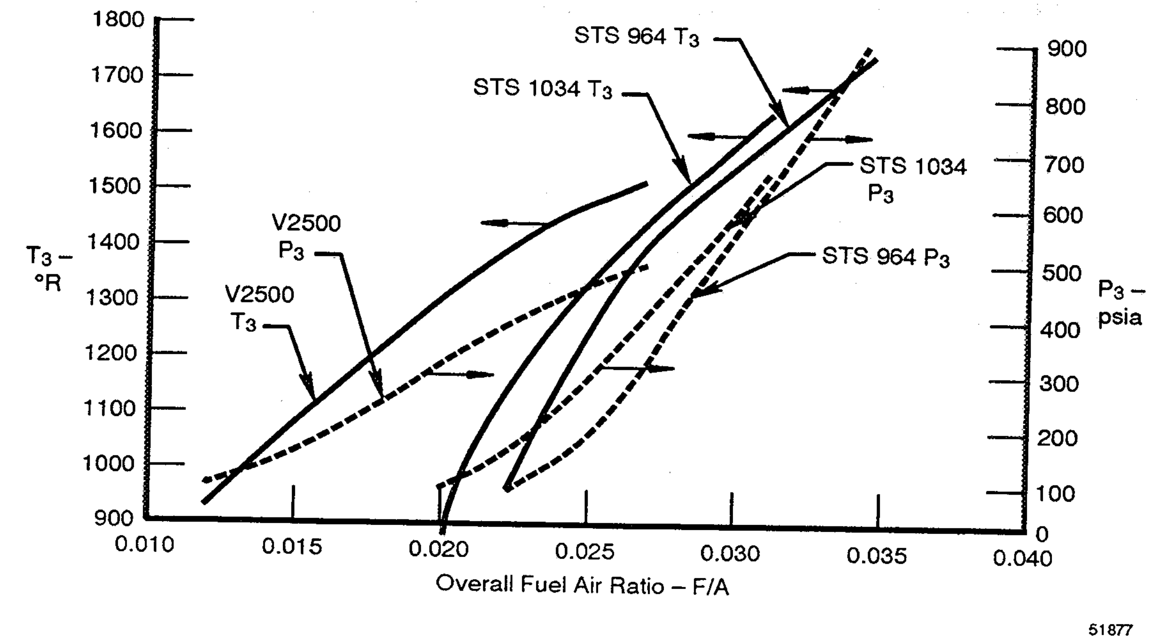


Figure 4–14. *Station 3 Temperature and Pressure Versus Fuel/Air Ratio for V2500-A5, STS1034, and STS964*

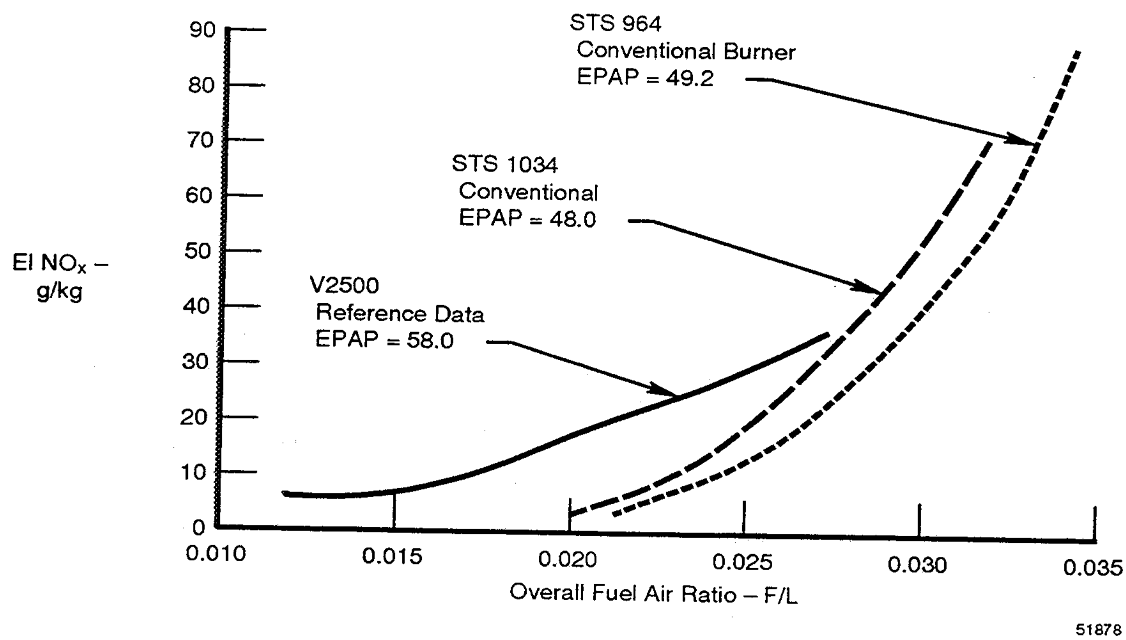


Figure 4–15. *EI NOx Versus Fuel/Air Ratio for V2500 Reference Burner and STS1034, STS964 Conventional Burner*

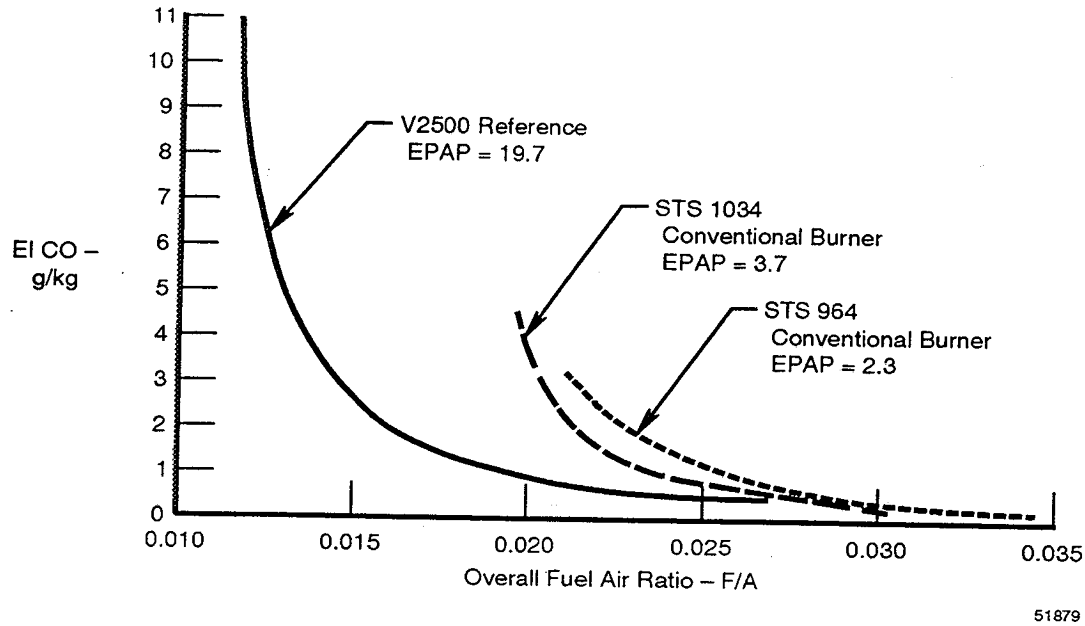
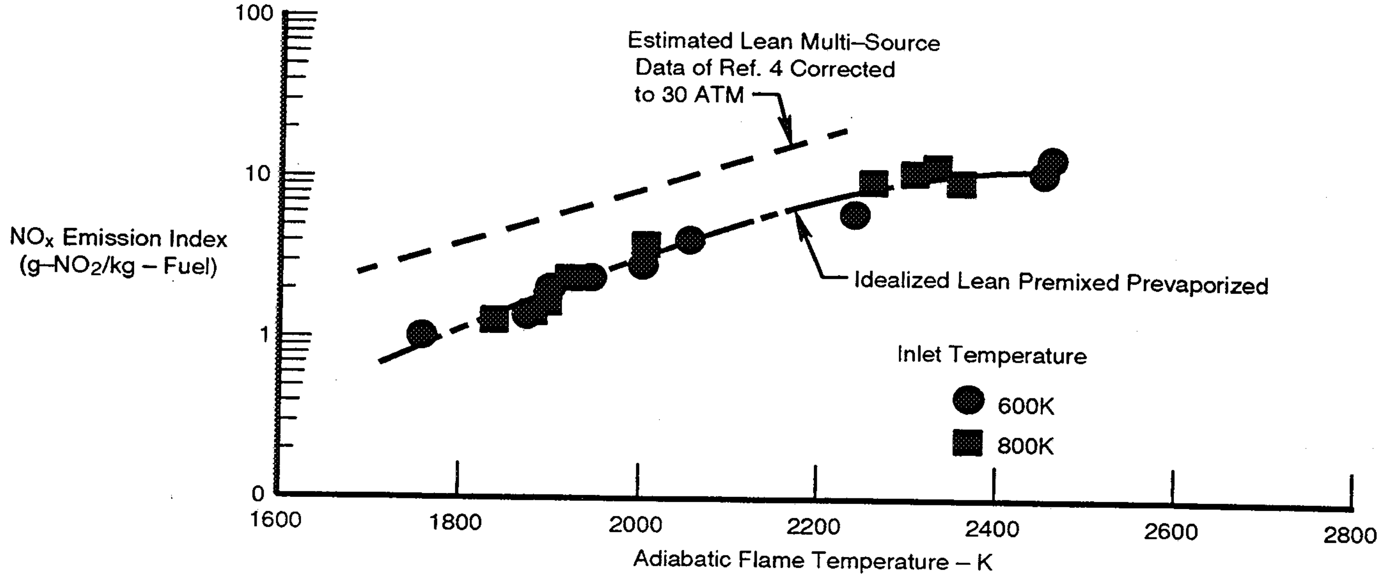


Figure 4–16. EI CO Versus Fuel/Air Ratio for V2500 Reference Burner and STS1034, STS964 Conventional Burner

4.3.2 Emissions Estimating Procedures for Lean Multisource Combustors

Assessment of emissions reduction potential for the lean multisource combustor concept is performed for NO_x only. The CO emissions from these combustors are assumed to be similar to those for the ASC, whose stoichiometry is assumed similar. The definition of NO_x emissions characteristics for lean multisource combustors is based on two sets of data from independently conducted experiments. The first, which applies to lean premixed, prevaporized systems, is based on the results of measurements obtained in an idealized lean premixed, prevaporized laboratory combustor. This particular experiment was that conducted by General Applied Sciences Laboratory and reported in detail in NASA CR 159421 (Reference 3). Since these tests precluded the influence of fuel vaporization on mixture uniformity by the use of gaseous propane fuel, the methodology involved establishing the equivalent NO_x EI on the basis of computed combustion zone adiabatic flame temperature. At various power levels, the adiabatic flame temperature in the active reaction zone was determined from the equivalence ratio power level schedule. The selected NO_x emissions data had been obtained at a combustor residence time of 2 milliseconds at 30 atmospheres pressure. These idealized lean premixed, prevaporized data are shown on Figure 4–17.



Correlation of NO_x Emission Index for 2 Msec Residence Time With Adiabatic Flame Temperature (P = 30 atm)

From General Applied Science Laboratory Data NASA CR–159421

51880

ADP Engine Adiabatic Flame Temperature - K		
	STS1034	*STS964*
Idle	2189	2213
Approach	2069	2129
Climb	1947	1992
Takeoff	2027	2174
Cruise	1878	2030

Figure 4–17. Laboratory Scale Measurements in an Idealized Lean Premixed Combustor

The second data set used for defining the NO_x characteristics of lean multisource combustors applies to the lean multisource approach. This data set, superimposed on the data of the first set in Figure 4–17, was produced by a multisource rig using representative small scale fuel injector/swirler components (Reference 4). Emissions were related to adiabatic flame temperature in much the same way as described in the preceding paragraph. The raw data were obtained at 10 atmospheres, so the square-root pressure correction factor from Equation 12 was applied to adjust the data to be consistent with the 30 atmosphere reference pressure of Figure 4–17. A tabulation of adiabatic flame temperatures at the various points in the STS964 and STS1034 lean multisource combustors is included in Figure 4–17.

4.3.3 Emissions Estimating Procedures for RQL Combustors

For the RQL combustor, NO_x and CO scaling procedures were similar to those for the conventional combustor: NO_x was assumed to vary with pressure and humidity according to Equation 12, with temperature effects based on experimental trends; CO was assumed to vary inversely with pressure according to Equation 13. The previously mentioned warning concerning the assumptions for NO_x pressure dependency is also applicable here.

All projections of emissions characteristics for the RQL combustor were referenced to data characteristics currently being generated in the small-scale HSR combustor rig, modified by the assumption that those tests will eventually achieve the HSCT goal of NO_x EI of 5.0 at supersonic cruise.

4.3.4 Emissions Estimating Procedures for Rich Catalytic Combustors

For rich catalytic combustors, emissions analyses used the reactor network approach shown on Figure 4–18. The pilot and lean-burn main reactor are considered well-stirred reactors, and the catalytic reactor bed is considered a plug-flow reactor. The MARK2X code was used for simplicity. The network was constrained by limitations of MARK2X, and by the representation and crude sizing of components. No account was taken of unmixedness effects on emissions. The resulting distribution in the components of the combustor emissions generation at takeoff power is tabulated on Table 4–4. At high power, the lean-burn main reactor generates most of the NO_x, while at idle power most NO_x is generated in the pilot. The calculations lack account of prompt NO_x generation, which may be significant at the low-temperature fuel-rich conditions in the rich catalyst bed.

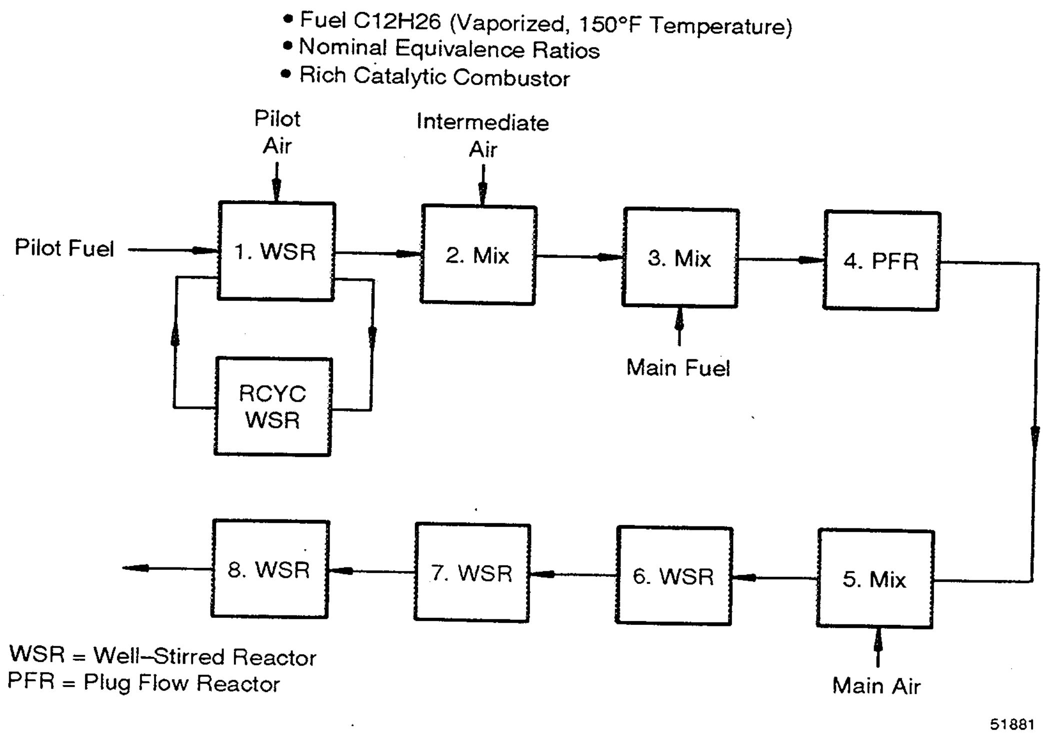


Figure 4–18. Emissions Estimates — Kollrack Reaction Mechanism for JP Fuel

Table 4–4. Rich Catalytic Combustor Distribution of Emissions Generation (Takeoff Power)

Pollutant EI (gm/kg)	Pilot	Catalyst Bed	LBMR
NOx	0.376	0.188	9.233
CO	0.179	82.73	1.592
UHC	0.0	Large	0.144

4.3.5 Emissions Estimating Procedures for Lean Catalytic Combustors

For the lean catalytic reactor, emissions analyses used a reactor network approach similar to that used for the rich catalytic reactors. The lean catalyst bed was taken to be a plug-flow reactor. The overall equivalence ratio was converted to the slightly higher *effective equivalence ratio* in accordance with the mixedness parameter procedures of Reference 3.

4.4 LINER COOLANT SAVINGS WITH ADVANCED CERAMIC MATERIALS

Liner cooling is recognized as a fundamental constraint on the design of low-emissions combustors. Use of combustor air for cooling purposes is counter to the need for lean mixtures for flame temperature control and combustor exit temperature quality. The reference combustor coolant levels are inadequate for cooling conventional FLOATWALL panels at STS964 conditions, but the coolant flow levels in the STS964 baseline and ASC configurations can be decreased by 4 percent of combustor airflow with the use of advanced ceramic materials derived from the EPM program. At the less severe STS1034 conditions, the baseline and ASC designs retain the reference FLOATWALL liner on the assumption that ongoing improvements by the year 2008 will achieve adequate liner durability with the same coolant levels as currently used in the reference V2500 liner.

With the technology maturation date for 75:1 pressure ratio engine cycles such as the STS964 nearly 20 years in the future, some liberty can be exercised in the definition of advanced materials for combustor liners in these applications. Using the current EPM program as a guideline, and recognizing that this program is targeting a nearer-term technology readiness date, it appears realistic to assume the availability of a ceramic matrix composite (CMC) with a working temperature capability of 2500°F, which could meet the liner life goals of this reference engine. The thermal conductivity for the CMC is projected to be about equal to that of current metallic FLOATWALL panels, which is somewhat higher than desirable. The CMC materials are not brittle, and therefore could be formed into large panels, but cannot be formed with pins. The CMC panels are envisioned as full FLOATWALL panel size, smooth slabs with no pins, with temperature capability to 2500°F, and thermal conductivity equal to that of metal.

Thermal analyses and design assessments to establish the cooling requirements for a CMC liner in the STS964 were accomplished by first performing specific liner coolant analyses to evaluate a reduced level of coolant flow, which would result in a maximum surface temperature of 2500°F on a conventional FLOATWALL panel, then demonstrating that a smooth slab CMC panel at the same coolant flow and maximum temperature would require reasonable slab thickness and reasonable backside coolant flow gaps for adequate heat transfer coefficients.

Analytic results for the STS964 baseline combustor showed that the reference FLOATWALL liner tended to run 250°F hotter than in the V2500. Incorporating a 2500°F advanced ceramic liner allowed a coolant reduction of 4 percent of combustor airflow.

For the STS1034 Baseline combustor, analytic results showed only a 100°F increase in FLOATWALL metal temperature. Retaining the V2500 coolant levels for the STS1034 is considered acceptable.

4.5 SMOKE REDUCTION AND REVISED EMISSIONS BY ADDING FRONT END AIR

The results of the combustor liner design study were used to refine the interpretation of the STS964 conventional baseline combustor. The elevated pressure and fuel-air ratio of the STS964 cycle might increase smoke. Pratt & Whitney combustor experience has many times indicated that a small increase in primary zone airflow can reduce smoke substantially. Since the availability of advanced ceramic materials resulted in a potential reduction in liner cooling requirements, adding this air to the primary zone as a precautionary measure against possibly higher smoke in the ADP cycles was deemed appropriate. Data relating primary zone airflow and smoke were obtained in the V2500 emissions development effort. These data were employed in this study to assess the impacts of the addition of air to the primary zone. Air was added in both conventional and ASC configurations.

4.5.1 Emissions Revisions with Leaner Primary in STS964 Conventional Combustors

The scaling of predicted smoke and emissions behavior with a leaner primary zone in the STS964 conventional combustor, relative to the V2500 reference data, is reasonably straightforward because both combustors have initially fuel-rich primary zones which will respond similarly to an increase in primary zone airflow. Figure 4–19 presents a curve showing the relative NO_x formation rate as a function of equivalence ratio. Adding 4 percent air shifts higher power combustor operation to a leaner equivalence ratio which causes an increase in NO_x emissions. The NO_x is assumed likely to increase 10 percent, as occurred in the V2500. At idle, the equivalence ratio change is dissimilar to the V2500 in that the STS964 idle equivalence ratio remains on the rich side of stoichiometric after the addition of 4 percent air. Thus, a scaled prediction for CO emissions in the STS964 with added air cannot be readily evaluated based on V2500 experience, and a net change of zero is bookkept. Results in this study for the STS964 baseline combustor reflect the configuration with 4 percent primary airflow addition.

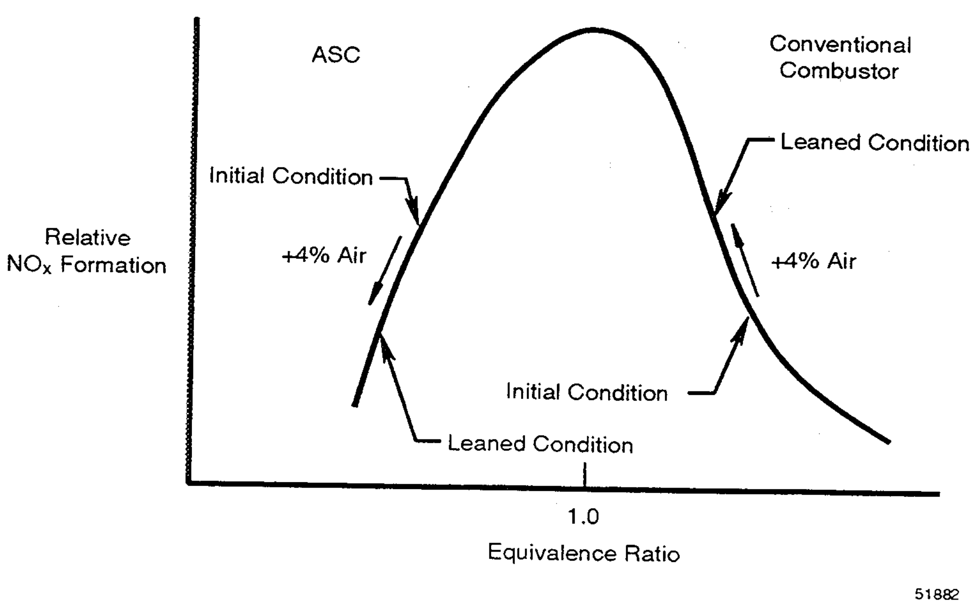


Figure 4–19. Relative NO_x Formation is a Strong Function of Equivalence Ratio

4.5.2 Emissions Revisions with Leaner Primary in STS964 Axially Staged Combustors

Air was added to the pilot stage of the ASC. The scaling of predicted leaner primary zone behavior of smoke and emissions in the STS964 ASC is accomplished with similar considerations regarding the changes in primary zone equivalence ratio and flame temperature. Since the pilot stage and the main stage are flow-connected in series, some of the 4 percent W_{ab} will also flow through the primary zone of the main stage. Both stages will therefore experience a desirable reduction of smoke. For simplicity of discussion, the full 4 percent is considered added to both stages. Because the ASC operates with both pilot and main stage on the lean side of the stoichiometric peak (Figure 4–19), addition of air results in movement of the operating points to still lower equivalence ratios and lower NO_x levels. A reduction of 10 percent, as for the conventional combustor, is assumed. However, the ability to realize this NO_x reduction is dependent on the stability of the pilot.

Similar observations are made to deduce that the CO emissions will increase, because both the pilot and the main stages move away from the empirical CO optimum equivalence ratio (near 1.0) when air is added. The magnitude of the CO increase is assumed to be 20 percent based on V2500 results.

4.6 FUEL SYSTEM CONSIDERATIONS FOR ADVANCED COMBUSTORS

The high pressure and temperature levels of the STS964 and STS1034 cycles present several unique and challenging problems regarding the design of the fuel supply system. Thermal control to prevent coking is a persistent worry for all the proposed combustor configurations, and is particularly of concern with the lean primary multisource concepts, in which the fuel flow in any one injector is far too low to be able to provide the fuel self-cooling commonly depended upon in conventional designs for coke prevention. Other fuel system considerations pertinent to the advanced combustors of this study are presented below.

One significant area of concern is the fuel pump. The maximum fuel pump capability of current technology is approximately 1400 psi. The STS964 is estimated to require a pump of at least 2000 psi capability, and the STS1034 will need at least 1800 psi pump capability. Fuel pump development is required. One potential candidate is a centrifugal system under study that possesses, in addition to higher pressure capability, the advantage of reduced heat input into the fuel, which is attractive from a coking point of view.

The STS964 fuel injector scaled from the V2500 fuel injector has been previously discussed in Section 4.1.1. The V2500 fuel injector flow number ($W_f/\sqrt{\Delta P}$) was assumed to be retained for the STS964 injector. A reduction in flow number would be advantageous for coke-prevention heat transfer, but would aggravate the 2000 psi pump capability development requirement.

The ability of the STS964 ASC to be staged at sub-idle power, with both the pilot stage and the main stage in operation at all flight conditions, is a big advantage. Many safety features and failsafe valve design considerations are greatly simplified when staging does not have to be performed in flight.

The complex fuel manifolding and the coking concerns of the lean multisource concept previously stated in Section 4.2.1 is a significant technological barrier. None of the other fuel system problems discussed above is considered a technology barrier.

5.0 RESULTS

Emissions projections for oxides of nitrogen (NO_x) and carbon monoxide (CO) were evaluated for the STS964 and the STS1034 performance cycles corresponding to entry-into-service (EIS) years of 2015 and 2008. A total of six low-emissions combustor concepts of progressively more aggressive technology were analyzed. These were:

- Conventional
- Axially-staged (ASC)
- Lean, multisource
- Rich-quench-lean (RQL)
- Rich catalytic
- Lean catalytic.

Because the STS1034 cycle was introduced late in the program, the STS964 cycle is the primary basis for comparison of candidates. However, since both cycles are for high bypass ratio (BPR) advanced ducted propulsor (ADP) engines, emissions behavioral trends were very similar. Hence, the relative ranking is valid for both cycles.

The STS1034 and the STS964 cycles both exhibit the narrow fuel-air ratio operating range of ADPs relative to turbofans. The relatively high fuel-air ratio (f/a) at idle is caused by requirements of fan driving power for the large increase in BPR at idle in an ADP engine. This feature is attractive to advanced technology concepts because it reduces demand for staging and/or variable geometry in low-emissions combustors.

5.1 COMPLETE EMISSIONS TABULATIONS

The complete presentation of tabulated NO_x and CO results for all of the candidate combustors at STS964 conditions compared to V2500 data is given in Tables 5–1 and 5–2. The corresponding presentation of tabulated NO_x and CO results for all of the candidate combustors at STS1034 conditions compared to V2500 data is given in Tables 5–3 and 5–4. The pertinent key features of these results which lead to ranking conclusions are discussed in more detail in Section 5.2..

Table 5–1. Emissions Tabulation of Complete Results of NO_x for STS964

	Emissions Index (EI) g/kg						*Current Allowables ICAO EPAP g/kN*	
	Idle	*Approach*	*Climb*	*Takeoff*	*Cruise*	*EPAP g/kN*	*Infinite Engine Limit*	*1 Engine Limit*
Current V2500-A5 Performance								
V2500 Reference Burners								
Conventional V2500-A5 Engine Data	5.0	10.1	27.1	33.8	14.7	58.0	105	90
ASC Full-Annular Rig Data	5.2	7.1	17.0	19.4	9.0	39.7		
Candidate Combustors for Advanced Ducted Propeller Engine Performance								
Scaled Combustors								
Conventional Burners								
Scaled % W_{AB}	3.5	17.5	45.7	89.0	33.2	49.2		
+4% W_{AB} Primary Zone (Baseline)	3.9	19.2	50.3	97.9	36.5	54.1		
ASC Burners								
Scaled % W_{AB}	1.75	8.75	22.3	44.5	16.6	24.6		
+4% W_{AB} Primary Zone (Baseline)	1.59	7.95	20.1	40.5	15.0	22.1	160	137
Conceptual Combustors								
Enhanced Lean-Burning Combustion								
Lean Multi-Source	7.36	9.0	8.6	21.2	7.1	16.0		
Lean Premixed Prevaporized	2.65	3.65	3.21	8.46	2.79	6.1		
Rich-Quench-Lean								
RQL	0.4	2.4	7.1	15.2	5.3	7.8		
Catalytic Combustion								
Rich Catalytic	5.3	2.9	3.5	9.2	2.1	7.7		
Lean Catalytic					0.8	1.4		

Table 5–2. Emissions Tabulation of Complete Results of CO for STS964

	Emissions Index (EI) g/kg						Current Allowables ICAO EPAP g/kN	
	Idle	*Approach*	*Climb*	*Takeoff*	*Cruise*	*EPAP g/kN*	*Infinite Engine Limit*	*1 Engine Limit*
Current V2500-A5 Performance								
V2500 Reference Burners								
Conventional V2500-A5 Engine Data	10.95	1.81	0.52	0.45		19.7	118	96
ASC Full-Annular Rig Data	4.1	11.1	4.0	4.4		20.0		
Candidate Combustors for Advanced Ducted Propeller Engine Performance								
Scaled Combustors								
Conventional Burners								
Scaled % W_{AB}	3.1	0.84	0.37	0.24		2.3		
+4% W_{AB} Primary Zone (Baseline)	3.1	0.84	0.37	0.24		2.3		
ASC Burners								
Scaled % W_{AB}	23.0	8.0	5.2	5.1		19.4		
+4% W_{AB} Primary Zone (Baseline)	27.6	9.6	6.2	6.1		23.3	118	96
Conceptual Combustors								
Enhanced Lean-Burning Combustion								
Lean Multi-Source						< 3.0		
Lean Premixed Prevaporized						< 10.0		
Rich-Quench-Lean								
RQL	30.4	4.8	1.3	0.2		19.7		
Catalytic Combustion								
Rich Catalytic	1.3	1.4	0.9	1.6		2.0		
Lean Catalytic						< 10.0		

Table 5–3. Emissions Tabulation of Complete Results of NO_x for STS1034

	Emissions Index (EI) g/kg						Current Allowables ICAO EPAP g/kN	
	Idle	Approach	Climb	Takeoff	Cruise	EPAP g/kN	Infinite Engine Limit	1 Engine Limit
Current V2500-A5 Performance								
V2500 Reference Burners								
Conventional V2500-A5 Engine Data	5.0	10.1	27.1	33.8	14.7	58.0	105	90
ASC Full-Annular Rig Data	5.2	7.1	17.0	19.4	9.0	39.7		
Candidate Combustors for Advanced Ducted Propeller Engine Performance							127	103
Scaled Combustors								
Conventional Burners								
Scaled % W_{AB} +4% W_{AB} Primary Zone (Baseline)	2.6	10.3	44.4	60.7	25.7	48.0		
ASC Burners								
Scaled % W_{AB} +4% W_{AB} Primary Zone (Baseline)	1.6	5.8	22.2	30.5	12.8	24.0		
Conceptual Combustors								
Enhanced Lean-Burning Combustion								
Lean Multi-Source	6.32	6.64	6.62	10.8	4.05	13.4		
Lean Premixed Prevaporized	2.23	2.66	2.76	4.57	1.35	5.3		
Rich-Quench-Lean								
RQL	0.3	1.3	6.8	9.1	4.7	7.1		
Catalytic Combustion								
Rich Catalytic								
Lean Catalytic								

Table 5–4. Emissions Tabulation of Complete Results of CO for STS1034

	Emissions Index (EI) g/kg						*Current Allowables ICAO EPAP g/kN*	
	Idle	*Approach*	*Climb*	*Takeoff*	*Cruise*	*EPAP g/kN*	*Infinite Engine Limit*	*1 Engine Limit*
Current V2500-A5 Performance								
V2500 Reference Burners								
Conventional V2500-A5 Engine Data	10.95	1.81	0.52	0.45		19.7	118	96
ASC Full-Annular Rig Data	4.1	11.1	4.0	4.4		20.0		
Candidate Combustors for Advanced Ducted Propeller Engine Performance								
Scaled Combustors								
Conventional Burners								
Scaled % W_{AB}	4.28	1.13	0.40	0.33		3.7		
+4% W_{AB} Primary Zone (Baseline)								
ASC Burners								
Scaled % W_{AB}	30.4	9.0	4.8	5.0		28.1		
+4% W_{AB} Primary Zone (Baseline)							118	96
Conceptual Combustors								
Enhanced Lean-Burning Combustion								
Lean Multi-Source								
Lean Premixed Prevaporized								
Rich-Quench-Lean								
RQL	40.4	8.2	1.4	0.9		31.5		
Catalytic Combustion								
Rich Catalytic								
Lean Catalytic								

5.2 OVERVIEW OF CANDIDATE CONCEPTS

A comparative summary of the cruise NO_x emissions index (EI) for all the candidate combustors is shown in the histogram of Figure 5–1. A more complete version of this summary, including NO_x Environmental Protection Agency Parameter (EPAP) values, is provided in Table 5–5. From Figure 5–1, the ranking is clear regarding the advanced combustor concepts, which have the capability to reduce cruise NO_x substantially below the current V2500-A5/D5 level, providing the assumed pressure dependencies are valid. Table 5–5 shows that even a conventionally designed baseline combustor produces NO_x EPAP values no higher than the current V2500-A5/D5 level of 58 g/kN.

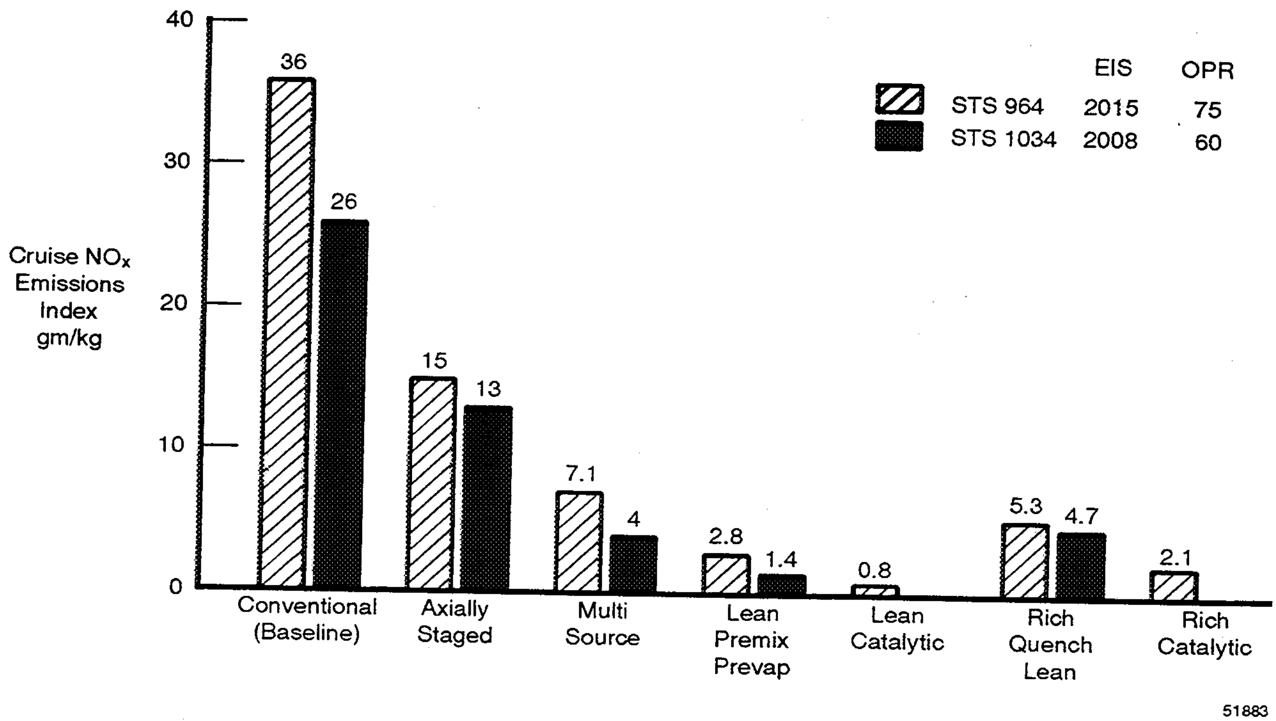


Figure 5–1. Cruise NO_x Emissions of Candidate Combustors

***Table 5–5.** NO_x Emissions from Advanced Ducted Prop Engines Comparative Summary Overview*

	STS 964 NOx EPAP (g/kN)	*STS 964 Cruise NOx EI (g/kg)*	*STS 1034 NOx EPAP (g/kN)*	*STS 1034 Cruise NOx EI (g/kg)*
Current ICAO Regulation Combustors	160	N/A	127	N/A
Conventional Combustor (Baseline)	54.1	36.5	48.0	25.7
Axially Staged Combustor	22.1	15.0	24.0	12.8
Idealized Lean Premixed, Prevaporized	6.1	2.8	5.3	1.4
Lean Multi-Source	16.0	7.1	13.4	4.0
Rich/Quench/Lean	7.8	5.3	7.1	4.7
Rich Catalytic	7.7	2.1	—	—
Lean Catalytic	1.4	0.8	—	—

To provide a proper perspective to the cursory observations evident on Figure 5–1 and Table 5–5, Figures 5–2 through 5–9 present a focused summary of the principal NO_x and CO emissions for each of the candidate combustors, including comments regarding various design advantages and/or disadvantages of the concept. Figure 5–2 summarizes the V2500-A5/D5 certification emissions and represents current technology for this study. Figure 5–3 presents the projections of current technology emissions levels to the advanced cycles under consideration. For both advanced cycles, NO_x EPAP is somewhat lower than the reference engine level, while CO EPAP is reduced considerably, by virtue of the relatively high idle level unique to the ADP cycles. Cruise NO_x EI level is somewhat higher than the reference engine level, however. For the STS1034 application, the cycle increases liner metal temperatures by 100°F relative to the V2500. This is acceptable, assuming moderate improvements in cooling technology and materials by the EIS year of 2008. The STS1034 baseline combustor therefore retains the reference combustor airflow distribution. For the STS964 application, the cycle increases liner metal temperatures by 250°F relative to the V2500. Ceramic matrix composite (CMC) material with a 2500°F capability is assumed by the EIS year 2015, allowing the cooling air requirement to be reduced by 4 percent of combustor airflow, which was in turn added to the primary zone for smoke control.

The STS964 baseline conventional combustor is summarized on Figure 5–4. Because of the extra front end airflow, NO_x emissions increased by 10 percent, but are still acceptable. This figure, and the remainder of the focused summary figures, are given only for the STS964 cycle.

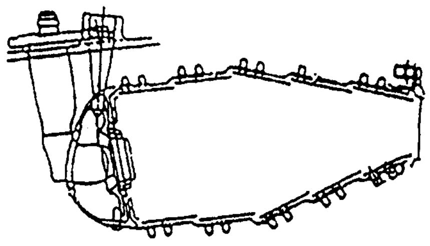
Figure 5–5 summarizes the results for the STS964 cycle with an ASC combustor. The NOx EPAP value of 22.1, and the cruise EI value of 15.0 are both less than half the NO_x levels of the baseline combustor. The CO EPAP increases considerably due to the lean primary zones in both the pilot and main stages, but still remains well below the regulatory limit.

Figure 5–6 presents a summary for the lean multisource combustor relative to idealized lean premixed, prevaporized emissions. Lean premixed, prevaporized emissions are acknowledged to be very low, but there are major technological barriers to be overcome. Achieving truly premixed, prevaporized combustion in an aircraft engine is considered not practical because of the potential danger of autoignition. Attempts to approach the lean premixed, prevaporized stoichiometry by using multiple injectors requires injector inventions and extremely complex fuel manifolding with multiple zone fuel staging. For example, the complexity can be emphasized by considering that the STS964 version depicted in the figure requires 336 injectors and the STS1034 version would require 504 injectors. During various flight segments, many of these injectors would have to be turned off. Further, absolute fuel flow to each injector would be too low to provide adequate self-protection from coking. However, the concept of approaching lean premixed, prevaporized stoichiometry by intense development with a practical number of improved injectors is considered to be a potential avenue of future research.

Figure 5–7 summarizes RQL results. The NO_x EPAP value of 7.8 g/kN, which is based on High Speed Research (HSR) program data extrapolated to achieving the High Speed Civil Transport (HSCT) goal of an NO_x EI of 5 g/kg at cruise, is less than 15 percent of the EPAP of the baseline STS964 combustor. The corresponding EPAP for CO is seen to be about 20 g/kN, high relative to the baseline combustor, but about equal to typical levels in current engines and well below the regulatory limit. The ongoing HSR program, the mixer development from the HSCT program, and the materials development from the Enabling Propulsion Materials Program, are expected to successfully demonstrate the emissions potential of this concept for long-term applications. However, there are aspects of its design execution (e.g., length) that may limit its practical applicability.

Figure 5–8 shows the emissions results of the rich catalytic combustor approach at STS964 conditions. The NO_x EI at cruise is about one-half that of the previously discussed RQL combustor. This reduction, which was projected at all high-power conditions, is primarily due to the rich-burning equivalence ratio of the catalytic reactor being significantly higher than the rich-burning zone of the RQL combustor (2.75 versus 1.9). The NO_x EPAP of the rich catalytic combustor, however, is almost the same as that of the RQL combustor. This is because of elevated NO_x at idle due to the torch-ignitor pilot, and, with development, this may be reduced. The CO emissions are seen to be well below the allowable limit, and are substantially lower than the RQL CO. This concept is considered to require long-term development of catalytic reactor technology, and also is dependent on successful mixer development from the HSCT program.

Figure 5–9 shows the emissions summary for the lean catalytic combustor at STS964 conditions. The NO_x results are the lowest of all combustor concepts examined in this study, and are considered to be the ultimate achievable. The CO EPAP value of less than 10 was simply assumed to be the same as was previously estimated for the lean premixed, prevaporized approach. However, because the lean catalytic concept is not self-starting, it is not deemed practical for aircraft engines.



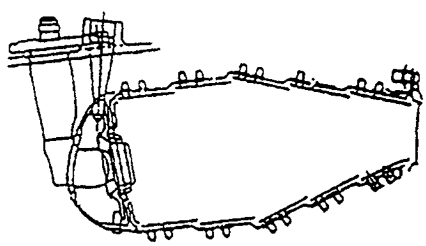
	NOx EPAP gm/kN	Cruise NOx EI gm/kg	CO EPAP gm/kN
Combustor	58.0	14.7	19.7
Current ICAO Regulation	105.0	N/A	118.0

Comments:

- Emissions are measured engine–certification test data.
- Single–stage, rich primary zone.
- Single–pipe, aerating fuel injectors.
- Liner is segmented FLOATWALL ® construction.
- Representative of current technology.

51859

Figure 5–2. V2500 A5 Conventional Burner Emissions Certification — 30,000 lb Thrust



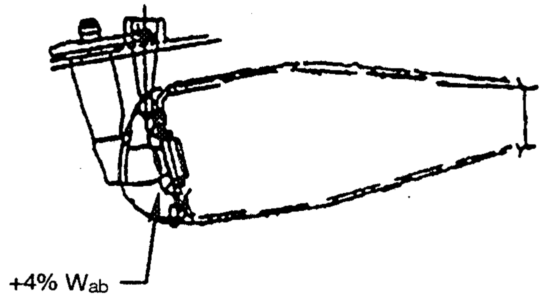
Engine Cycle	OPR	BPR	EIS Year	NOx EPAP gm/kN	Cruise NOx EI gm/kg	CO EPAP gm/kN
V2500–A5	33	5	1993	58.0	14.7	19.7
STS 1034	60	20	2008	48.0	25.7	3.7
STS 964	75	25	2015	49.2	33.2	2.3

Comments:

- STS 1034 – Cycle increased liner metal temperatures 100°F over V2500.
  STS 964 – Cycle increases liner metal temperatures 250°F over V2500.

51892

Figure 5–3. Advanced Low Emissions Subsonic Combustor Study — Current Technology Combustor in Advanced Technology Engine Cycles



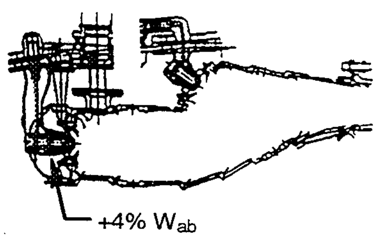
	NO_x EPAP gm/kN	Cruise NO_x EI gm/kg	CO EPAP gm/kN
Combustor	54.1	36.5	2.3
Current ICAO Regulations	160.0	N/A	118.0

Comments:

- Advanced ceramic matrix composite liner saves 15% Wcool (4% W_{ab}).
- 4% W_{ab} added to primary zone for smoke control.
- NO_x emissions increase by 10% because 4% W_{ab} front end air leans the rich primary zone.
- This configuration is considered the STS 964 Baseline.

51891

Figure 5–4. *STS964 Conventional Baseline Burner — Projected Emissions 61,800 lb Thrust Rating*



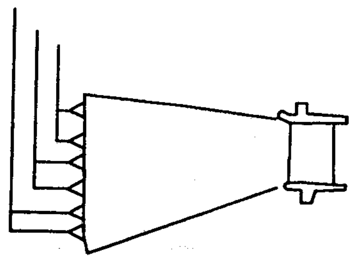
	NO_x EPAP gm/kN	Cruise NO_x EI gm/kg	CO EPAP gm/kN
Combustor	22.1	15.0	23.3
STS 964 Baseline	54.1	36.5	2.3

Comments:

- Two combustion stages, both globally lean–reduces NO_x.
- 4% W_{ab} added to pilot primary zone for smoke control.
- NO_x emissions decrease by 10% because 4% W_{ab} added front end air further leans both primary zones.
- NO_x emissions less than 1/2 baseline.
- CO emissions increase by 20% because of leaner primary zones.
- CO EPAP is still acceptable.
- Fuel system staging occurs during acceleration to idle. Combustor is staged for all steady state operating conditions.

51893

Figure 5–5. *STS964 Axially Staged Combustor — Projected Emissions 61,800 lb Thrust Rating*



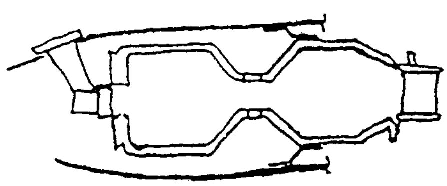
	NO_x EPAP gm/kN	Cruise NO_x EI gm/kg	CO EPAP gm/kN
Idealized LPP	6.1	2.8	<10
Lean Multi–Source	16.0	7.1	<30
STS 964 Baseline	54.1	36.5	2.3

Comments:

- Idealized LPP based on gaseous fuel combustion experiments.
  - Requires inventions.
  - Autoignition and stability risks.
- Multi–source is possible approach.
- Complex fuel system (336 sources/coking risk).
- Injector inventions required.

51894

Figure 5–6. STS964 Enhanced Lean Burning — Projected Emissions 61,800 lb Thrust Rating



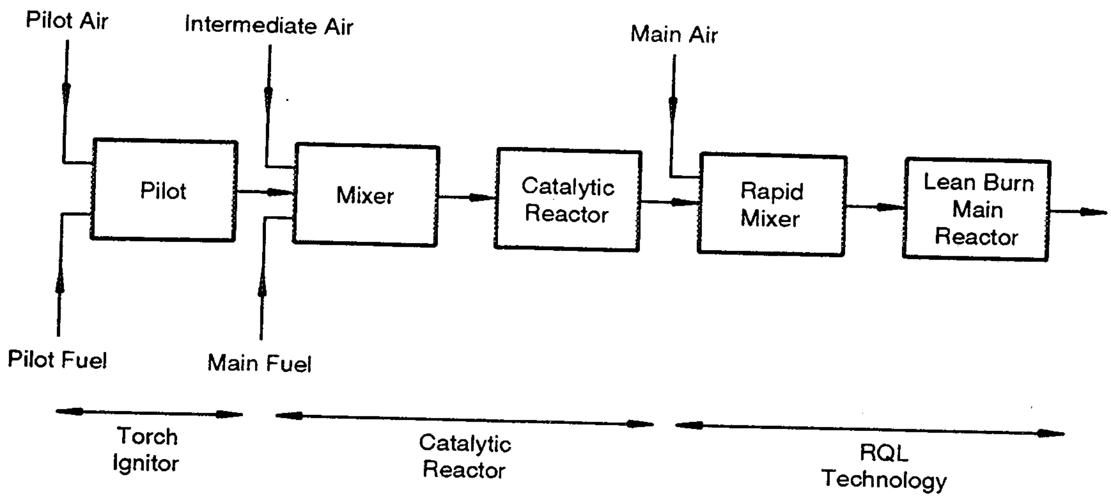
	NO_x EPAP gm/kN	Cruise NO_x EI gm/kg	CO EPAP gm/kN
Combustor	7.8	5.3	<20
STS 964 Baseline	54.1	36.5	2.3

Comments:

- Combustor definition based on High Speed Research program.
- No variable geometry or fuel staging required.
- Long section length required.

51895

Figure 5–7. STS964 Rich/Quench/Lean — Projected Emissions 61,800 lb Thrust Rating



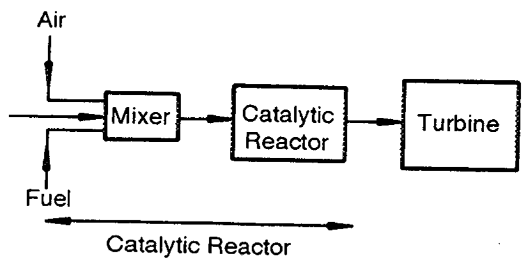
	NO_x EPAP gm/kN	Cruise NO_x EI gm/kg	CO EPAP gm/kN
Combustor	7.7	2.1	2.0
STS 964 Baseline	54.1	36.5	2.3

Comments:

- Requires rich/quench/lean aerothermal and materials technology from High Speed Research program.
- Requires catalytic reactor development.
- Futher reduction in low power NO_x should reduce EPAP.

51871

Figure 5–8. *STS964 Rich Catalytic — Projected Emissions 61,800 lb Thrust Rating*



	NO_x EPAP gm/kN	Cruise NO_x EI gm/kg	CO EPAP gm/kN
Combustor	1.4	0.8	<10
STS 964 Baseline	54.1	36.5	2.3

Comments:
- Extremely low NO_x emissions considered to be ultimate levels.
- Requires substantial catalytic reactor material advances.
- Homogeneous mixture critical to success but autoignition precludes premixing.

51870

Figure 5–9. STS964 Lean Catalytic — Projected Emissions 61,800 lb Thrust Rating

6.0 BARRIER TECHNOLOGIES

In addition to the general fuel system development concerns expressed in Section 4.6, and the need for advanced ceramic matrix composite liner material development from the ongoing Enabling Propulsion Materials (EPM) Program for liner durability in STS964 combustor liners, the major development areas for the individual combustor concepts are summarized below.

6.1 CONVENTIONAL COMBUSTORS

The conventional combustors presented are used as a baseline relating the advanced combustors to current technology. Although the emission estimates for conventional combustors at advanced ducted propulsor (ADP) performance were tolerable by current International Civil Aviation Organization Committee on Aviation Environmental Protection (ICAO/CAEP) regulations, they are too high for consideration as optimum advanced combustors. Although not specifically evaluated in this study, the generation of smoke would be a concern in the fuel-rich primary zone of a conventional combustor operating at the high pressure and fuel-air ratios of the advanced cycles. The liner material improvements of FLOATWALL™ and advanced ceramics for the axially-staged compressor (ASC) combustors also apply to the conventional combustor.

6.2 AXIALLY STAGED COMBUSTORS

FLOATWALL improvements by the entry-into-service (EIS) year 2008 are required for liner durability in the STS1034 ASC liner.

6.3 LEAN MULTISOURCE COMBUSTORS

Autoignition dangers make achieving true premixed, prevaporized injection unrealistic. This ideal injection can only be approached through improved injectors with refined mixing.

The immediate incorporation of most of the combustion airflow through the fuel injectors implies very low liner coolant airflow. Substantial advances in liner materials will be required.

There is a need for technology advancements to produce combustor air-fuel admission components that yield homogeneous mixtures from a mechanically more compact envelope (i.e., one with higher airflow to frontal-area ratio).

Fuel distribution manifolding is extremely complex for the multitude of injectors in the Lean Multisource Concepts studies. The design of a fuel distribution system capable of providing coke free operation with a large number of fuel sources in the thermal environment of either the STS1034 or the STS964 engines is considered a substantial technological barrier.

6.4 RICH-QUENCH-LEAN COMBUSTORS

While there are no strong technological barriers associated with the rich-quench-lean (RQL) combustor, the concept is dependent on the ongoing High Speed Research Combustor Development Program. Smoke generation at the high rich-burn equivalence ratios is a concern. The ceramic liner material is dependent on the advanced ceramics development of the ongoing EPM ceramic materials program.

6.5 RICH CATALYTIC COMBUSTORS

The good fuel-air mixing necessary prior to the catalyst bed inlet is dependent on the High Speed Civil Transport (HSCT) mixing development in progress for the RQL. Unmixedness prior to catalyst bed inlet adversely effects emissions, durability, and autoignition.

Because autoignition is a concern, further development of catalytic reactor technology is required, and better materials for the catalyst bed are essential. Rapid mixer, lean-burn main reactor technologies, and design rules must wait for mixer development from HSCT efforts. Packaging (overall length) with the catalytic reactor is also a concern. In general, the future development requirements for the rich catalytic combustor are long-term efforts. Development of design techniques for successfully integrating ceramic components (the catalytic reactor bed) into engine systems is necessary.

6.6 LEAN CATALYTIC COMBUSTORS

Homogeneous mixing is critical to success, but autoignition precludes premixing. Extensive mixer development is required.

Catalyst bed temperatures must equal full combustor exit temperature. Substantial catalytic reactor material advances are essential.

The future development requirements for the lean catalytic combustor are generally considered to be long-term efforts.

7.0 CRUISE EMISSIONS MEASUREMENTS

A study was undertaken to examine suitable methods for the evaluation of aircraft engine emissions at altitude cruise conditions. The effort encompasses reviews of current methods for translating sea-level engine emissions data to altitude cruise conditions and candidate methods for actual measurement of emissions at cruise. These efforts reported herein parallel closely the present status of similar studies currently in process by the International Civil Aviation Organization Committee on Aviation Environmental Protection (ICAO/CAEP). Study conclusions at the present time are:

- Current standardized procedures employed by Pratt & Whitney (P&W), General Electric Aircraft Engines (GEAE), and Rolls Royce for calculating cruise oxides of nitrogen (NO_x) emissions from sea-level test data use similar methodologies and give essentially equivalent results
- Boeing and Snecma have developed a simplified fuel flow correlation method that is promising
- Favored technique for near-term development of measured cruise emissions is to measure critical engine performance data during actual cruise.

7.1 CURRENT METHODOLOGY FOR CRUISE EMISSIONS CALCULATIONS

The current basis for emissions calculations are the database curves of emissions indices of carbon monoxide (CO), THC, and NOx versus T_3 or fuel-air ratio (f/a) obtained experimentally from sea-level engine testing for power settings ranging from subidle through takeoff. Calculations of cruise emissions indices then follow the recommended formulations given in Section 7.1.3 of the International Standards and Recommended Practices document (Reference 6). The pressure, temperature, and f/a terms needed for scaling from sea-level to altitude conditions are obtained from engine performance tables and scaling factors derived from parametric combustor rig tests.

For CO and THC, P&W scales sea-level data to altitude conditions, employing pressure scaling with an exponent of 1.0 (as previously given in Equation 13). For NO_x, P&W uses the temperature, pressure, and humidity scaling previously given in Equation 12. Other engine manufacturers use basically the same equations with slightly different values for the constants and exponents. Snecma uses two methods for NOx: one based on temperature, pressure, and airflow, and a second based on fuel flow. Boeing also uses a calculation procedure based on fuel flow. All of these various calculation procedures produce essentially equivalent predictions of cruise NO_x emissions index (EI) for current conventional engines, as shown by a set of comparative calculations performed by P&W for an ICAO/CAEP international study. A second international study calculation by another manufacturer showed a similar equivalency of results among the various methods for engines that had assumed NO_x reductions of 20 and 40 percent via combustor modifications. A representative portion of the set of calculations performed by P&W is summarized on Table 7–1 and Figure 7–1.

Table 7–1 tabulates the aircraft operating parameters of thrust, time-in-mode, altitude, and Mach number for a typical mission of 3000 nautical miles for a wide body aircraft powered by PW4000 engines. Figure 7–1 presents NO_x levels predicted by the various methods under study. The various methods produce nearly equivalent predictions that differ from one another by approximately 15 percent at most. Note that the abscissa of the plot only represents flight segment and has nothing to do with data differences. The fuel-flow methods are promising approaches for determination of NO_x at altitude, because they offer an additional means of estimating cruise emissions from data that can be readily measured inflight at cruise altitude and do not require knowledge of proprietary engine performance data (e.g., combustor inlet temperature and pressure).

Table 7–1. *Flight Condition Points Selected for EI NO_x Method Comparison 3000 NM Mission (5561 KM)*

Point No.	Mode	Duration (minutes)	Altitude (feet)	Mn
1	Taxi	9.0	0.0	0.0
2, 3	Takeoff	1.30	0 – 1500	0.0 – 0.388
4 – 15	Climb 1	13.92	1500 – 35000	0.388 – 0.800
16 – 19	Cruise 1	202.18	35000	0.800
20, 21	Climb 2	9.27	35000 – 39000	0.800
22 – 25	Cruise 2	148.81	39000	0.800
26 – 35	Descent	24.06	39000 – 1500	0.800 – 0.197
36, 37	Approach	1.54	1500	0.388 – 0.197
38 – 41	Land	3.20	1500 – 0.0	0.197 – 0.0
42	Taxi	5.00	0.0	0.0

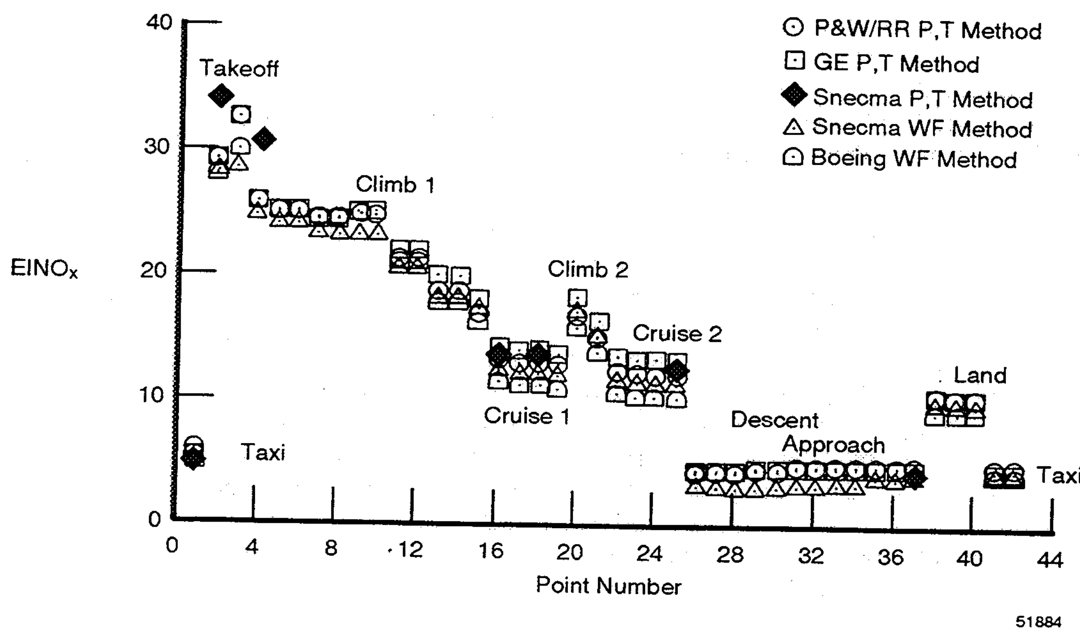


Figure 7–1. *EI NO_x Calculation Method Comparison — PW4000 3000 Nautical Mile Mission*

7.2 DIRECT MEASUREMENT OF EMISSIONS AT CRUISE

Candidate methods for obtaining altitude cruise emissions may be classed as follows:

- *Method 1* — Measure cruise emissions in an altitude-chamber engine test
- *Method 2* — Measure cruise emissions in flight with engine tailpipe sampling probes routed into the aircraft cockpit for onboard gas analysis with conventional emissions equipment
- *Method 3* — Measure cruise emissions in flight with nonintrusive spectrometrical viewing across the engine exhaust jet.

In addition to the current extrapolative method discussed in Section 7.1, Method 1 is now technically feasible and has been accomplished at the P&W Willgoos Test Laboratory. However, altitude-chamber testing is very expensive and is not recommended as an ongoing test procedure for regulatory monitoring of altitude emissions. Rather, this method is considered a valuable tool for calibrating other less expensive, preferred methods.

Method 2, the actual measurement of inflight emissions by tailpipe sampling, is not considered viable for near-term development applications. A brief internal study of this method by P&W considered the requirements for gas sampling and operation of emissions analyzing equipment in the cockpit at altitude. It was assumed that exhaust gas sampling could be done by mounting special probes at the current location of the exit gas temperature (EGT) probes. Although such probes have been used successfully at P&W for emissions sampling, they are not currently accepted by the regulatory agencies. Sampling validity would have to be demonstrated, but all other measurement procedures would be in compliance with the current ICAO international standards specified in Reference 6. Altitude considerations included the following:

- Satisfying of ICAO specifications on sample line diameter and transport time with the reduced-density gases at altitude
- Existing capability for achieving current regulations of line thermal control and orifice pressure drop with existing bypass pumps
- Required operation of the analyzer equipment at the subatmospheric pressure in the aircraft cabin.

Many of the problem areas are extensions of similar problems that have been addressed and resolved in the altitude test chamber Method 1. There are no insurmountable obstacles, but considerable development would be required. The basic routing of sampling lines from the tailpipe into the cabin and the handling of exhaust gases in the cabin would have to addressed. A fundamental question of whether the existing analyzer equipment operates reliably at a subatmospheric cabin pressure could be resolved with dedicated tests during an altitude chamber test. One unresolved question pertains to the current equipment requirement for AC electric power at 60 cycles, while flight engine power is normally generated at 400 cycles.

Nonintrusive methods have been proposed for inflight measurement of emissions. These proposed methods include making measurements through a window from inside the aircraft or from another aircraft. However, this approach is in its infancy, and major development and validation will be required before such a method can be considered.

8.0 TECHNOLOGY DEVELOPMENT PLAN

The Advanced Low Emissions Subsonic Combustor Study analytically investigated numerous concepts with the potential to significantly reduce oxides of nitrogen (NO_x) emissions in future high pressure ratio aircraft gas turbine engines that will enter into revenue service after the year 2000. The intent of this effort was to identify promising concepts and discover existing technological barriers to implementation, so a development program could be structured.

The thrust range covered by Pratt & Whitney (P&W) engines is presently about 4,000 lbf to 84,000 lbf and is being extended even further. Engine use covers both commercial and military applications. The vast majority of the applications are intended for subsonic cruise, with fighters and potentially the High Speed Civil Transport (HSCT) as exceptions.

With this diverse background of application, there is naturally an equally wide variety evident in the combustion systems that have been historically produced by P&W. The flowpath layouts extend from axial flow to reverse flow, and there is a wide range in physical sizes for the combustors. However, almost all recent combustors are annular in configuration.

Regardless of the intended application, the size, or even the layout, the combustion chamber of a gas turbine engine has to satisfy a common list of design requirements, as given in Table 8–1. There are typically several critical design points for the combustor where the requirements must be satisfied. To achieve the required performance, the combustion system must be designed to fit in a spatial envelope that is specified by a number of critical radii and a length (Figure 8–1). These critical dimensions will be determined by the rotating machinery aerodynamic designs, main shaft considerations, the arrangement of bearing compartments, and weight. Combustion considerations are able to exert only minor influence on the initial choices for these dimensions, and there is always a continual pressure to reduce the length of the combustion section of any engine.

Table 8–1. Combustion Chamber Design Requirements

All combustors should satisfy the following:
• Minimum pressure loss • High combustion efficiency • Wide stability limits • Suitable outlet temperature distributions • Adequate durability • Low exhaust emissions of smoke, carbon monoxide, and unburned hydrocarbons • Low weight • Low cost • Ease of maintenance.
Special requirements as needed:
• Emission of oxides of nitrogen (NO_x) • Multi-fuel • Life limits.

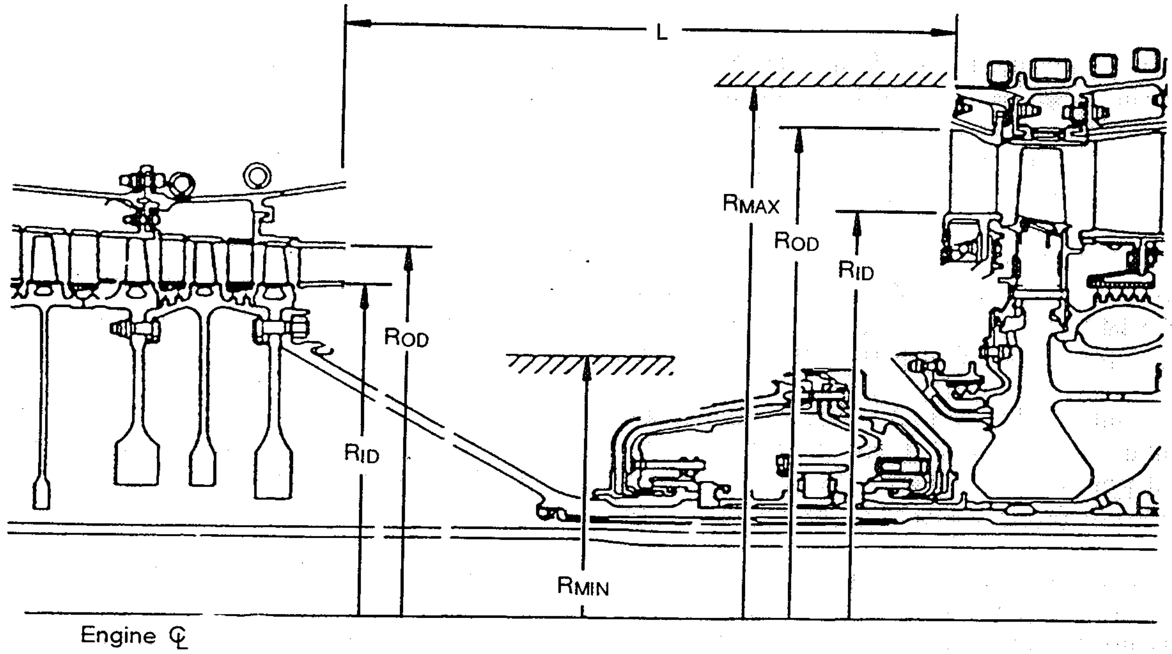


Figure 8–1. Cross-Section of Axial Flow Engine, Showing Constraints Applied to Combustion Chamber Envelope

The goals and difficulties are virtually the same for all combustors, with any differences being more of emphasis than of uniqueness. The historical challenge to the various designers has been to overcome these difficulties and thereby satisfy the goals within the constraints imposed by the particular size configuration or application. There was some evidence extant that suggested the constraints might lead to a convergence of the solutions as the goals became more ambitious and the difficulties more severe. Such a convergence might imply that a generic approach to solutions is viable.

A study has been made (Reference 9) to investigate how future engine goals and design constraints might drive combustor configurations and sizes toward a common approach. In this study, performance trends were considered for their tendency to drive towards a generic combustor characteristic for engines in the following aircraft classes:

- Military fighter/attack
- Military/commercial transport
- High-speed civil transport
- Military/commercial utility/rotorcraft.

Military/commercial utility/rotorcraft were not considered very extensively as engines, for such aircraft generally have the additional constraint of very small size. It was persuasively argued, however, that the combustors of all advanced engines will tend towards a common (small) size (Reference 10). Special purpose vehicles such as the National Aerospace Plane (NASP) form a category separate from main stream development. Special purpose vehicles were not considered because they do not rely on gas turbines for main propulsion.

Performance information and design goals for the aircraft classes considered in the study were taken from other studies.

The commercial supersonic transport performance information was based on P&W studies of an early 21st century HSCT aircraft (Reference 11). For the military/commercial transport, two sources were used. The first source was a NASA (Reference 12) extrapolation of existing commercial engine historical design trends to beyond the year 2000. This study, by its nature, assumes that the future is based on currently understood and available technology and is useful in identifying limiting technologies. The second source was an internal P&W 21st century engine study allowing for the appearance of new approaches based on extrapolation of base technologies. Such an engine might enter service in 2010. This study revealed that the propulsion system barriers and technology requirements are generally similar and are interrelated for all engine types (Reference 13) and that the gas generator is key to achieving higher performance (Reference 14). Pratt & Whitney approaches to the U.S. Government's Integrated High Performance Turbine Engine Technology (IHPTET) initiative were used for the future military fighter/attack aircraft. To cover the military/commercial utility/rotorcraft application, P&W Canada's advanced engine plans were used, together with NASA information, on a typical small-engine, IHPTET-type combustor (Reference 15).

For the different classes of aircraft, except the HSCT, Government and industry sources agreed extremely closely on design goals for increased engine power density and reduced specific fuel consumption. The future of engines will continue the historical trends of the past, and the classic demands made on the engine designer by the aircraft designer will continue unchanged. Engines must have more thrust and less weight and consume less fuel for a given frontal cross section.

The IHPTET goals do not specifically refer to exhaust emissions, except for an implicit goal of minimum visibility of the exhaust plume. In addition to smoke, IHPTET exhaust-plume visibility will probably involve brown trails due to NO_x generation in the combustor. For this reason alone, emissions control goals will almost certainly be included in IHPTET. The 21st century engine has emissions goals that are consistent with anticipated regulatory trends.

The study (Reference 10) showed that only engine cycle changes exert a direct influence on combustor design. The virtually common goals for future military and commercial engines result in similar approaches to changes to the thermodynamic cycle, and any differences again were more those of emphasis. To take advantage of possible performance improvements, engine pressure ratio, operating temperature, and bypass ratio should all be as high as possible, with application modifiers being engine weight and installed drag. Thus, when the combustor operating conditions for an advanced ducted propulsor (ADP) and an IHPTET-like combustor are compared, they are virtually identical. Table 8–2 makes such a comparison.

Table 8–2. Comparison of Combustor Operating Conditions for Future Engines

Ranges of Combustor Operating Conditions for P&W ADP Study Engine	
Inlet Pressure	22-44 atmos
Overall Fuel-to-Air Ratio (OFAR)	0.028-0.040
Overall Pressure Drop	3.5% inlet total pressure
Combustion Intensity	7-9 x 10^6 BTU/hr ft^3 atmos
Compressor Exit Mach Number	0.25-0.27
Leading Parameters for an Early, IHPTET-Like Study Combustor	
Compressor Exit Mach Number	0.3
Inlet Pressure	32.6 atmos
Inlet Temperature	1191°F (917K)
Airflow Rate	43 kg/s
Overall Fuel-to-Air Ratio (OFAR)	0.040
Liner Pressure Drop	3.0% Inlet Total Pressure
Combustion Intensity	8 x 10^6 BTU/hr ft^3 atmos
Combustor L/D	1.5
Mean Inlet Radius	216 mm

Combustors for the HSCT engine at design point (Reference 11) have high inlet temperatures due to intake ram effects and turbine inlet temperatures that are fairly high (but lower than subsonic engines because maximum thermal efficiency occurs at these lower values due to the intake ram effects). However, overall pressure ratios are down compared to the other engines considered in this survey.

Once a cycle is decided, the envelope for the combustor (Figure 8–1) is determined by the layout choices of the rotating machinery, as indicated above. For the ADP study engines, a mean radius (R_{mean}) for the combustion section was found to be in the range of 250 mm, regardless of the core airflow. For the IHPTET study engines, a mean radius was found to be 210 to 220 mm; similarly, for the utility/rotorcraft application, the mean radius was 200 to 220 mm.

The convergence in mean combustor radii arises, in general, from the higher pressure ratios that are feasible for the larger power engines (a thrust/weight ratio effect) compared to those that can be achieved in the weight-limited lower power engines. For the utility/rotorcraft application, the mean radius is determined by the reverse-flow combustor arrangement that is typically used. For all engines, on the minimum radius (R_{min}) for annular combustion chambers there is a practical lower limit that is determined by the engine shafts and possible bearing compartment accommodation that must pass through the center of the system.

Finally, combustion systems for aircraft applications have to be capable of multipoint operations. Experience with small engines teaches that combustors with annular heights (H_d) less than about 50 mm rarely give satisfactory performance at high altitudes. This factor is usually established from altitude considerations and the need to accommodate a suitable number of conical-spray fuel injectors at a spacing that results in minimum pattern factor at high-power conditions. The combustor length (L_c) is generally determined from the space heating rate with the selected annular height, by considerations of idle-power combustion efficiency. The length is commonly expressed as a multiple of H_d and tends to be minimized to limit use of combustion air for liner cooling.

R_{mean}, R_{min}, L_c, and H_d appear to have practical minimum values, and combustors for future advanced subsonic engines appear to be converging on this generic size.

Due to its high-thrust, low-pressure, high-core airflow characteristic arising from supersonic cruise needs, the HSCT engine is physically large with a correspondingly large spatial envelope for the combustor. The relatively large value resulting for L_c is clearly inconsistent with the trend for all other future engines. This generous combustor length simplifies the packaging problems associated with reduced-emissions combustion concepts and allows approaches that are extremely difficult to apply in high-pressure, high bypass ratio engines. Application in advanced ducted propulsors, which represent the logical extension of this thermodynamic cycle, is especially difficult. Therefore, the combustion system for the HSCT emerges as an anomaly in future engine design trends, and some low emissions solutions that are attractive in this application might not be applicable in other applications.

Due to axial length requirements, these findings imply that a number of the concepts considered above (e.g., the rich/quench/lean [RQL] and rich catalytic systems) will be difficult to successfully package into future advanced engines for subsonic flight. Pratt & Whitney sees the ongoing low emissions research and development for these applications as more profitably continuing along two essentially separate paths of rich and lean combustion — each path with its own specific barriers, yet also some common concerns.

8.1 RICH COMBUSTION DEVELOPMENT

More aggressive rich combustion schemes (e.g., RQL and rich catalytic) are highly dependent on materials and the development of other technologies, some of which are proceeding under the EPM effort. Until these technologies become available, effort will be concentrated on RQL bounding studies, including a near-term rig investigation of limits of RQL combustion in the context of the subsonic ADP engine cycles under consideration. There are substantial differences between the ADP and HSCT (for which RQL is currently being evaluated) that have a direct impact on combustor section design.

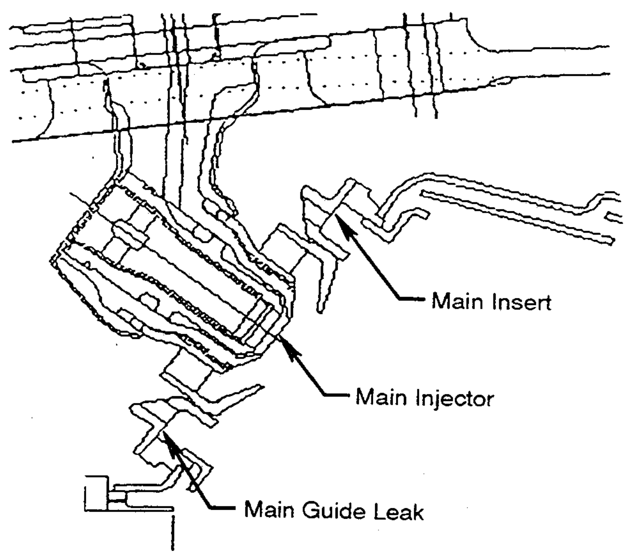
In view of this, P&W believes that near-term efforts in the rich combustion arena should be directed at a concept derived from experience with the axially-staged compressor (ASC), namely, rich free-shear layer combustion.

For inhouse development, P&W decided on a three-phase technology program plan to achieve continuing reductions in NO_x emissions (Reference 2). Phase I represented a conventional combustor with stoichiometry modifications to achieve modest NO_x reductions (Reference 5). Phase II was centered on a modified combustor with significant departures from conventional design but still using conventional base-technology to achieve more significant NO_x reductions (References 2, 16). The Phase III approach for larger-still NO_x reductions was defined as a combustor having major departures from conventional design, for which both research and technology development would be required.

Pratt & Whitney's Phase II approach, the ASC, uses fuel-staging to establish separate pilot and main stage burning zones. These burning zones are arranged so that effluent from the pilot enters the main. There are several important advantages to this arrangement (Reference 2). The burning zones both operate nominally fuel-lean on a bulk basis. In an engine demonstration, the ASC has achieved the desired significant reductions in NO_x emissions while holding emission levels of THC and carbon monoxide (CO) well below current regulations (Reference 16). The ASC achieves its emissions reductions through the fuel staging system; all other components used in the combustor represent essentially off-the-shelf technology. Therefore, the fuel, air, and product mixing levels remain unchanged from conventional combustors.

The fuel injectors incorporated in both burning zones of the ASC are airblast-atomizing types of conventional design. The numbers of injectors used in each stage were equal, and the number per stage was the same as that in the Phase I version of the combustor. Therefore, the total number of fuel injectors was doubled. However, this does not mean that the fuel loading per injector was halved, since the bulk of the fuel was reacted in the main burning zone, and the flow split between stages was not a constant with engine operating conditions.

When selecting the injectors for the pilot and main burning zones, no attempts were made to optimize their designs for their new functions. The atomization capability of the existing airblast injector design configuration was judged to be very satisfactory at all engine power conditions for use in both burning zones. The fuel injection package (Figure 8–2) for both pilot and main zones consists of the airblast fuel injector and an *insert swirler* that is mounted permanently on the combustor and surrounds the injector. The original purpose of the insert swirler was as a smoke-control device for the adjusted-stoichiometry (rich/lean) Phase I reduced-emissions combustor design (Reference 5). In this role, the amount of insert swirler air was only a few percent of the combustor total and was less than the amount used in the injector itself. Used in the ASC pilot burning zone, the insert swirler retains this form and function.



Note: Insert Swirler individual jets in general have compound angles to injector centerline; in this case, both angles are zero.

Figure 8–2. *Cross-Section of ASC Main Stage Fuel Injection Package, Showing Airblast-Atomizing Injector and Combustor-Mounted Insert Swirler*

When applied in the ASC main burning zone, the amount of insert swirler air is considerably increased over the value in the original use and now exceeds that introduced by the injector. This additional insert swirler air enhances an important characteristic observed in the Phase I application. In the Phase I combustor, the aerodynamic flowfield produced by the injector (designed to reduce THC by keeping unreacted fuel away from the combustor liner film cooling, through an inside-out recirculation pattern) is such that merged coswirling atomizing air jets, and the atomized liquid fuel contained therein, tend to be confined by the individual air jets produced by the insert swirler. This injector jet coherence is maintained until transverse combustion air jets from the liners are encountered (Reference

17). Confirmation of this behavior was obtained for both Phase I and Phase II injection packages through flame and spray observations made in combustors with high optical access at Wright Laboratory.

In the ASC main burning zone at typical engine takeoff power conditions, the injector (plus insertion leakage) equivalence ratio is approximately 5, and with inclusion of all of the insert swirler air, it is slightly greater than 2. Thus, the majority of the engine fuel, together with a portion of the air required to react it, is introduced into the main burning zone of the ASC as a number of extremely coherent, fuel-rich, swirling jets.

The hot combustion products directly entering the main burning zone from the upstream pilot zone provide an environment conducive to rapid liquid fuel spray evaporation. By this means, the finely-atomized, mainstage fuel contained within the coherent jets is quickly converted to a vapor, and some precombustion/partial combustion reactions take place at rich equivalence ratios.

Complete chemical reaction of the vaporized, partially-reacted, fuel-rich, coherent jets coproduced in the main burning zone takes place in the shear layers associated with these jets and the main zone combustion air jets introduced through the main zone liner walls, as free-standing flames. Therefore, although nominally a lean-lean system, the ASC may be viewed as being a lean-rich-lean system.

The effectiveness of the ASC in reducing NO_x therefore should be improved by increasing the rate at which reactants mix in the free-standing shear layers associated with the jet-system established by the aerodynamics of the main zone. By reactants in this context is meant fresh combustion air from outside, and the fuel-rich, partially reacted gases in the coherent injector jets. The intent would be to improve the quench of the reacting, fuel-rich, shear layers, not to improve the fuel/air mixing before reaction in the shear layers (i.e., to improve the existing rich/lean combustion characteristic of the main burning zone, not to convert it to better-mixed lean combustion). Such an attempt at lean burning without dramatically reducing the bulk equivalence ratio, together with major improvements in mixing, might actually increase NO_x emissions (Reference 7), as may be understood from Figure 8–3.

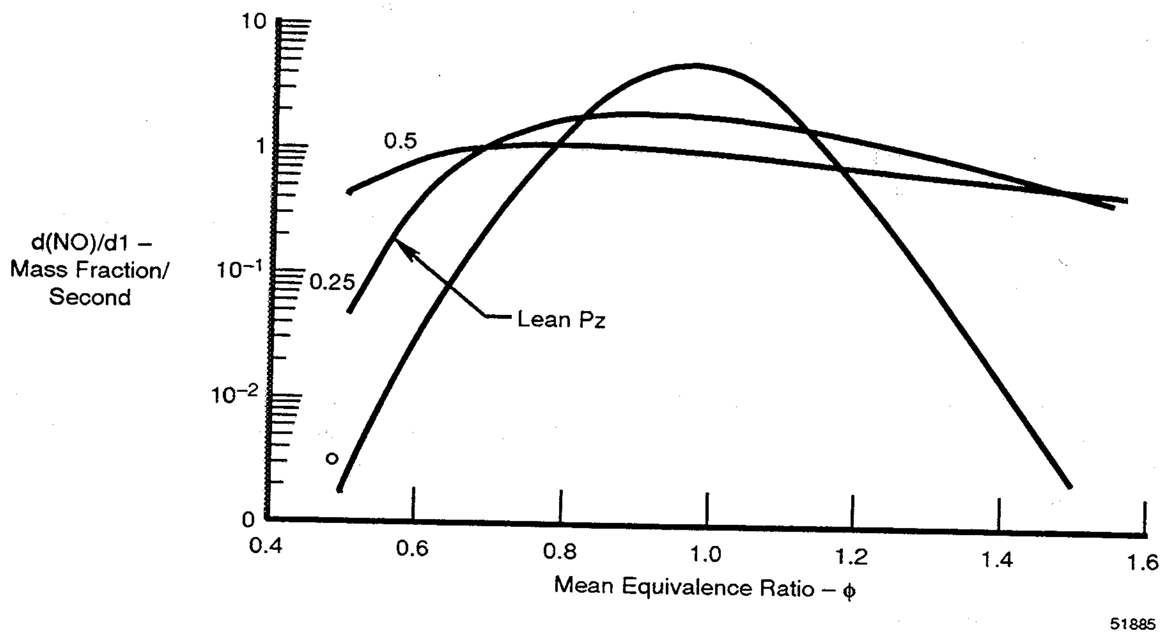


Figure 8–3. *Dependency of Rate of Formation of NO on Mean Equivalence Ratio and Unmixedness (Heywood & Mikus)*

Although they may be complex in shape and are certainly multiple in arrangement, the shear layers formed in the mainstage burning zone are most likely to follow classical shear layer behavior in general characteristics. Figure 8–4 shows an example of the isothermal shear layer mean axial velocities measured in a simplified research combustor (Reference 18), compared with a classical velocity profile. While the agreement is not perfect due to proscribed curvature effects, the agreement is fair. Keller & Daily (Reference 19) for premixed propane and air combustion have shown that shear layer structure is qualitatively essentially unchanged by heat release. However, Roy (Reference 20) has indicated that heat release can reduce shear layer entrainment. Even so, to first order, it may be taken that the ASC shear layers will follow accepted classical shear layer behavior.

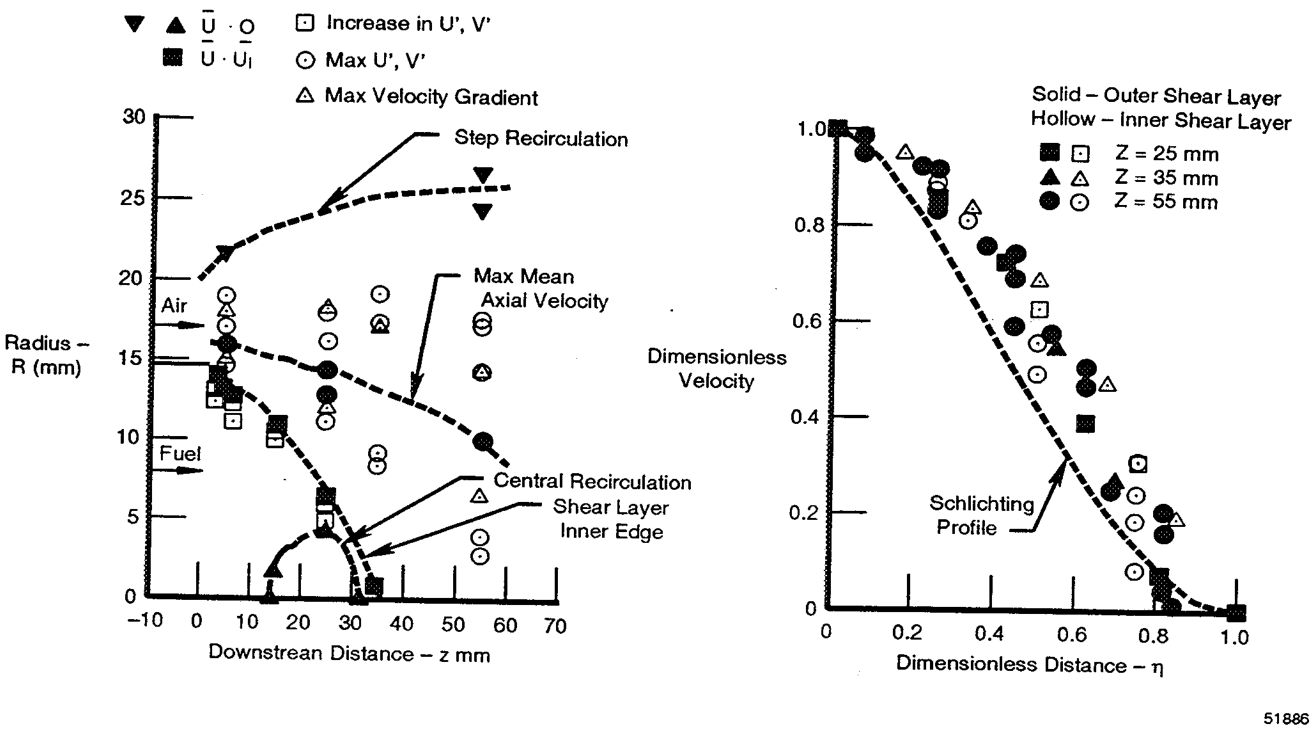


Figure 8–4. Shear Layers in Combustors; Examples for a Research Step-Combustor

The rate of mixing for shear layers is governed by free-stream entrainment. and this depends on the shear layer surface area and the momentum ratio across it (Reference 21). i.e.,

$$T_{mix} = C(M_1/M_2)^{0.5} A_{layer} \qquad \text{Equation 14}$$

Where

T_{mix} = mixing time
C = a constant
M = stream momentum
1, 2 = streams 1 and 2 constituting the shear layer
A_{layer} = stream face area

The momentum ratio across a shear layer in a combustor depends on the pressure drop across the combustor. and this is not a free variable. Efforts to improve mixing therefore are likely to concentrate on surface area (A_{layer}) increases and perturbations of shear layer vorticity (the constant C).

It can be shown (Reference 9) that the large-scale inviscid motions in the organized. time-dependent structures that make up shear layers (Figure 8–5). through their entrainment of pure fluid from either side of the layer, play a dominant role in establishing the environment leading to molecular-level mixing and subsequent chemical reaction, and hence, determine the distributions of mixed fluid or reaction products.

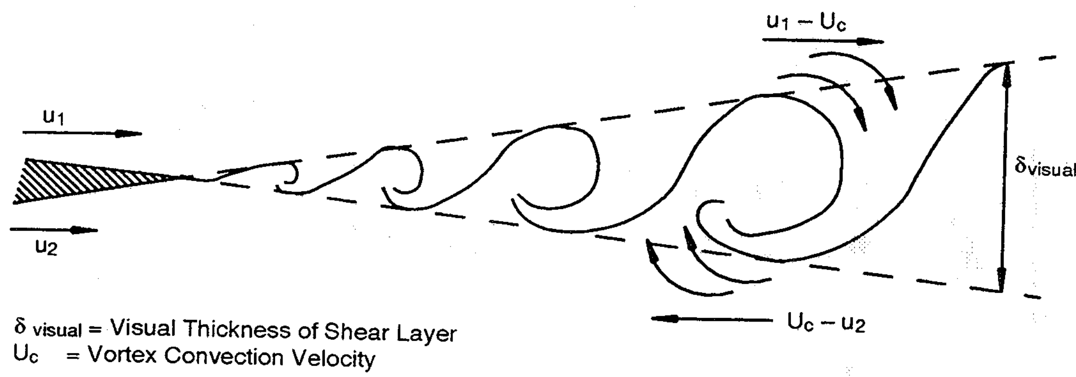


Figure 8–5. Shear Layer Dynamic Growth; Entrainment into a Spatially-Evolving Shear Layer

Entrainment is the process by which fluid is brought into the turbulent shear layer, where the large structures engulf high-speed/high-density and low-speed/low-density bounding fluids. Molecular mixing then takes place within the regions associated with the large structures, in a manner analogous to vortex breakdown. This behavior can be strongly influenced by the initial conditions of the shear layer, and the inherent instability of incompressible shear layers. Hence, the combustion efficiency of an individual reacting shear layer can, in principle, be controlled through manipulation of the initial conditions and/or the initiation, evolution, and interaction of the coherent structures. The combustion efficiency of a region as a whole may be controlled through changes to the extent/number/or proximity of the shear layers contained within it.

Although much has already been done, a program of basic research in isothermal flow is therefore desirable to investigate how axisymmetric shear layer mixing — with high-velocity, high-density fluid (representing the main zone fuel-rich, coherent injector jets) on one side of the layer and low-velocity, low-density fluid (representing the main zone general environment) on the other — may be advantageously manipulated and enhanced. The high-velocity, high-density stream should be seeded with particles to represent fuel droplets. Such a program should include the introduction through initial conditions, of local streamwise perturbations superimposed on shear layers. Such disturbances have been shown to be effective (Reference 9). The interaction of shear layers in close proximity to each other is also worthy of consideration (Reference 22). Useful exploitation of the unstable character of incompressible shear layers might be achieved, as has been demonstrated for particle-laden jets (Reference 23). Promising schemes could then be evaluated in simple reacting flow experiments, before full combustor demonstration.

8.2 LEAN COMBUSTION DEVELOPMENT

Although lean premixed, prevaporized and lean catalytic combustion offer the potential for very low NO_x, they were deemed to be impractical for aircraft engines. Lean direct injection in the form of lean multisource combustion was identified as an approach to be pursued. The fuel system (number of injectors and manifold/control complexity) and packaging barriers discussed previously must be addressed in bounding studies to determine the practical limits on the number of fuel injectors that can be accommodated in an economically viable commercial application. Attendant to these efforts are studies to assess the diffuser case implications of a large number of penetrations in the high-pressure and temperature environment of future ADP cycles, and fuel system coking impacts (considering the requirement for shutting off fuel flow to some of the injectors) during various flight segments. Once the definition of a practical lean multisource system has occurred, analysis will determine the levels of fuel injection quality and mixing necessary to optimize emissions reduction potential.

Fuel injection quality and mixing levels achieved can be characterized in terms of the Heywood mixing parameter, S (Reference 7), where:

$$S = \sigma/\overline{\phi} \qquad \text{Equation 15}$$

And

σ = Standard deviation for a Guassian distribution about the mean
$\overline{\phi}$ = Mean equivalence ratio

Empirical data on Heywood's mixing parameter for current conventional combustion systems are shown in Figure 8–6.

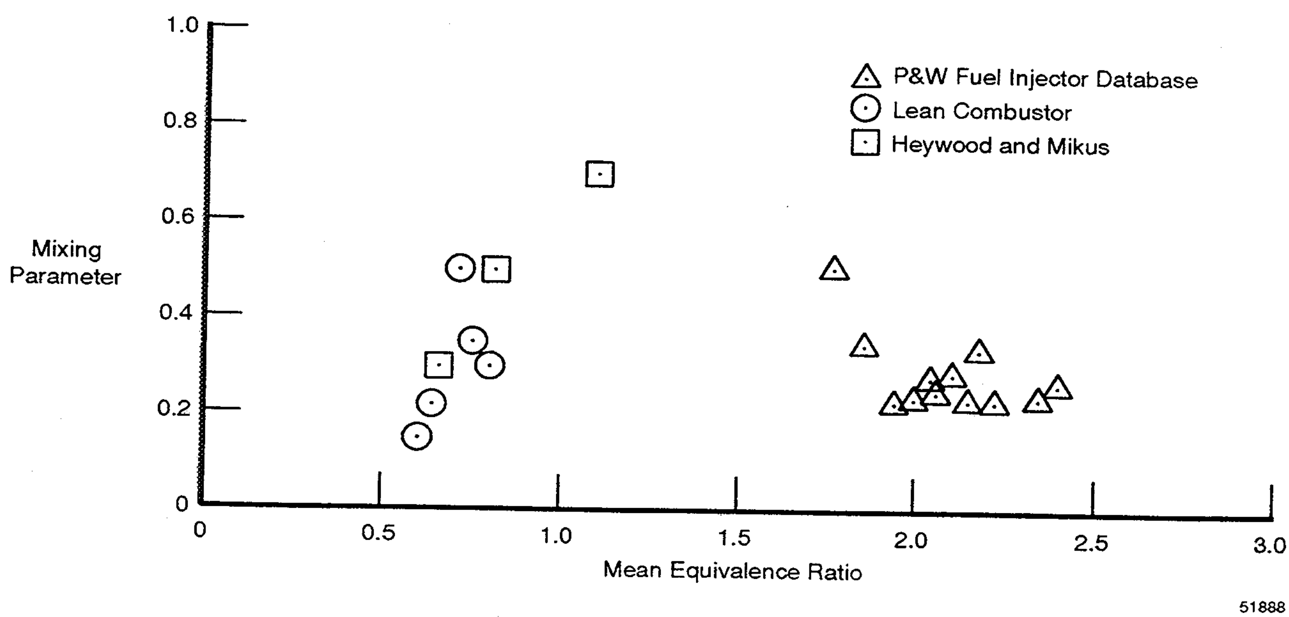


Figure 8–6. Empirical Data on Heywood's Unmixedness Parameter for Conventional Engine Combustors

The term S is made up of two components: $S_{injection}$, associated with the way fuel is introduced to the combustion air, and S_{energy}, associated with the total energy available for mixing (i.e., the air pressure drop across the combustor for airblast atomization of the liquid fuel). However, the combustor pressure drop is not a free variable due to its impact on engine cycle performance.

The effect of fuel-air unmixedness on NO_x emissions has been described by Heywood and Mikus (Reference 7), and at least partially substantiated experimentally by Lyons (Reference 8). Figure 8–3 shows the calculated effect of unmixedness on the rate of formation of NO. If very lean or very rich combustion occurs, improving mixing (reducing S) decreases the rate of NO formation. For a substantial range of fuel-lean and fuel-rich equivalence ratios about the stoichiometric value, improving mixing actually increases the rate of formation of NO.

These data provide the basis for selecting the stoichiometry of a future lean multisource combustor to never exceed an equivalence ratio of 0.6. This ensures that improving fuel-air mixing is advantageous for reducing NO_x. Mixing would have to be improved so that the width of the equivalence ratio probability distribution function (PDF) is decreased to the point where none of the fuel is reacted at or near stoichiometric conditions. Figure 8–7 illustrates this principle, expressed in terms of flame temperatures.

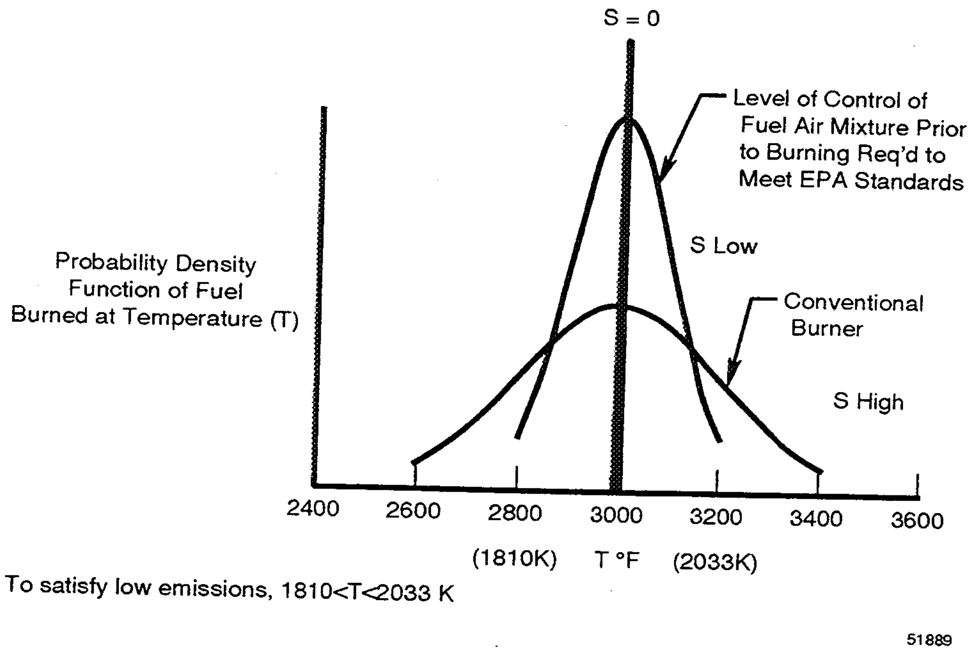


Figure 8–7. Illustration of Effects of Unmixedness Through Flame Temperature PDF

Following the bounding studies, effort will shift to development of improved, compact, packagable fuel injection systems that can achieve the homogeneous, low S fuel-air mixtures discussed above. Out of necessity, past fuel injector design has always been driven by requirements for excellent stability characteristics for obvious flight safety reasons. Unfortunately, the features that result in highly stable combustion (rich fuel-air mixture pockets) are antithetical to low NO_x production. If stability can be ensured by other means (e.g., staging to ensure operation in a prescribed stable equivalence ratio region, an independent energy source, or a small complement of stable fuel injectors), fuel injectors designed for enhanced fuel-air mixing can be used to provide the low S fuel-air mixture capable of achieving low NO_x. The development of these injectors should involve cold flow air and simulated fuel distribution studies involving candidate concepts fabricated by fast prototyping procedures such as stereo lithography. Ultimately, flame tube experiments should be conducted with likely configurations to establish hot performance potential and effects of pressure on NO_x emissions. The establishment of pressure scaling effects is important, since the operating pressures of the advanced cycles under consideration will probably far exceed the capability of existing facilities used for sector and annular rig testing. The NO_x/pressure relationship has been shown to vary considerably with configuration and equivalence ratio. A thorough understanding is necessary to preclude the investment of scarce resources on inappropriate concepts.

Following the low S injector development effort, attention should be directed at integration of the selected configuration(s) into a practical, lean, multisource prototype combustor. This device will employ both fuel and air staging to accomplish the strict combustor equivalence ratio management necessary to achieve low NO_x. It relies heavily on the LET 22 HSR variable geometry efforts to produce a reliable concept to control front end stoichiometry, as described below.

In an aircraft gas turbine engine, the combustor must satisfy a number of critical operability design requirements, in addition to achieving low emissions. The total requirements determine that the combustor must incorporate some local control over combustor equivalence ratio as engine power varies. Staging is therefore a necessity if the range of operating equivalence ratios becomes wide, as it does when low emissions considerations are added to the design requirements. If the maximum allowable equivalence ratio is determined to be 0.6 from an emissions point of view, then both fuel staging and air staging can be necessary, depending on the engine thermodynamic cycle.

Table 8–3 shows the results of a study on the combustor staging needed to satisfy both operability and emissions requirements in the ADP engine STS 1034. This engine is scheduled for possible service introduction around the year 2008. The burning zone equivalence ratio was selected to be 0.9 at sea level idle power and 0.6 at takeoff power. An idle equivalence ratio of 0.9 was selected to insure low CO and THC emissions, and acceptable stability/operability characteristics.

Table 8–3. *Study of Combined Fuel and Air Staging in an ADP Engine 1034 for Service in 2008 AD*

Thrust	***P3***	***T3***	***Wab***	***FAR***	***PHI***	***EPAP***	***FPb***	***Wafle***
7.00	60.80	888.00	13.20	0.02	0.29	0.68	6.47	0.65
30.00	194.50	1223.00	39.73	0.02	0.34	0.36	7.14	0.77
Cruise	248.10	1481.00	46.41	0.03	0.42	—	7.20	0.76
85.00	536.40	1594.00	98.07	0.03	0.43	0.62	7.30	0.76
100.00	638.10	1662.00	113.91	0.03	0.46	0.24	7.28	0.76

Thrust	***ACd fle***	***Del P/P***	***% INJ***	***PHI fle***	***PHI Local***	***Wa lln***	***ACd lln***	***Del P/P***
7.00	16.38	0.055	50.00	0.90	0.59	0.35	10.17	0.040
30.00	25.33	0.039	66.67	0.67	0.51	0.23	10.17	0.024
Cruise	25.33	0.039	100.00	0.55	0.42	0.24	10.17	0.024
85.00	25.33	0.040	100.00	0.57	0.43	0.24	10.17	0.025
100.00	25.33	0.039	100.00	0.60	0.46	0.24	10.17	0.024

Notes:
Fuel: 3 stages; Air: on/off (no modulation), uncompensated.
Fuel and Air Staging: no modulation, staging subapproach.
STS 1034: Year 2008 advanced ducted propulsor 25% cooling and dilution.

To meet the design equivalence ratios with the performance characteristics of the study engine, both fuel and air staging is required. The air staging is an *On - Off* (no modulation) device, and there is no pressure drop compensation. The device is *Off* at idle power, and is *On* at all other power points. Combustor pressure drop is 4.0 percent at idle and is 2.4 percent at all other points. The engine should find this change acceptable without suffering severe specific fuel consumption penalties, or rematching the rotating machinery. The variable geometry is most conveniently applied to the fuel injectors, as the amount of air to be redirected by the variable geometry is about 10 percent of the total combustor air.

The fuel-staging system fuels only 50 percent of the fuel injectors at idle power, two-thirds of the injectors at approach power, and 100 percent of the injectors at all other power settings (i.e., it is a 3-stage system). The burning zone has an equivalence ratio of 0.9 at sea level idle power, and varies between 0.55 and 0.67 over all other power settings, with 0.6 being achieved at takeoff.

The effects of coking in the fuel injectors was the subject of a separate study for this engine. This study indicated a coke avoidance scheme would need to be incorporated, and that the number of injectors would most likely be greater than 20 and less than 60. As previously indicated, only direct injection devices were considered due to the potential safety hazards of premixed, or partially premixed systems.

The air and fuel-staged combustor described would be positioned to benefit greatly in terms of NO_x reduction from improvements in fuel-air mixing. The NO_x potential of such a combustor are levels that are only 15 to 25 percent of those for current combustor technology. While there is no denying that the proposed combustion system does involve a marked increase in complexity compared to conventional combustors, care has been taken to minimize, as far as possible, the impact on operability issues.

As an adjunct, EPM efforts, if successful, may provide a path for a significant reduction in cooling air requirements that will allow more air for stoichiometry control. As such, the design of the practical lean multisource combustor will consider two levels of liner cooling: the current Floatwall™ level of 25 percent, and a reduced level of 10 percent. The bounding studies conducted initially in the A.L.E. follow on will be reviewed to incorporate any appropriate new technological developments resulting from subsequent investigations.

8.3 DEVELOPMENT SCHEDULE

The program to accomplish these efforts is presented in Figure 8–8. As discussed above, it envisions two separate paths: one for the rich, and one for the lean approaches. Initially, these investigations will include analysis, design, and bench scale rig testing. This will be followed by sector rig evaluation. There are generic supporting studies, such as coke avoidance systems (including the experimental centrifugal fuel pump that may benefit in reduced fuel heat addition), having potential application in either approach. Both paths lead to an approach/configuration downselect at the end of 1996, that will ultimately lead to a mid 1999 high-pressure annular rig demonstration of program goals.

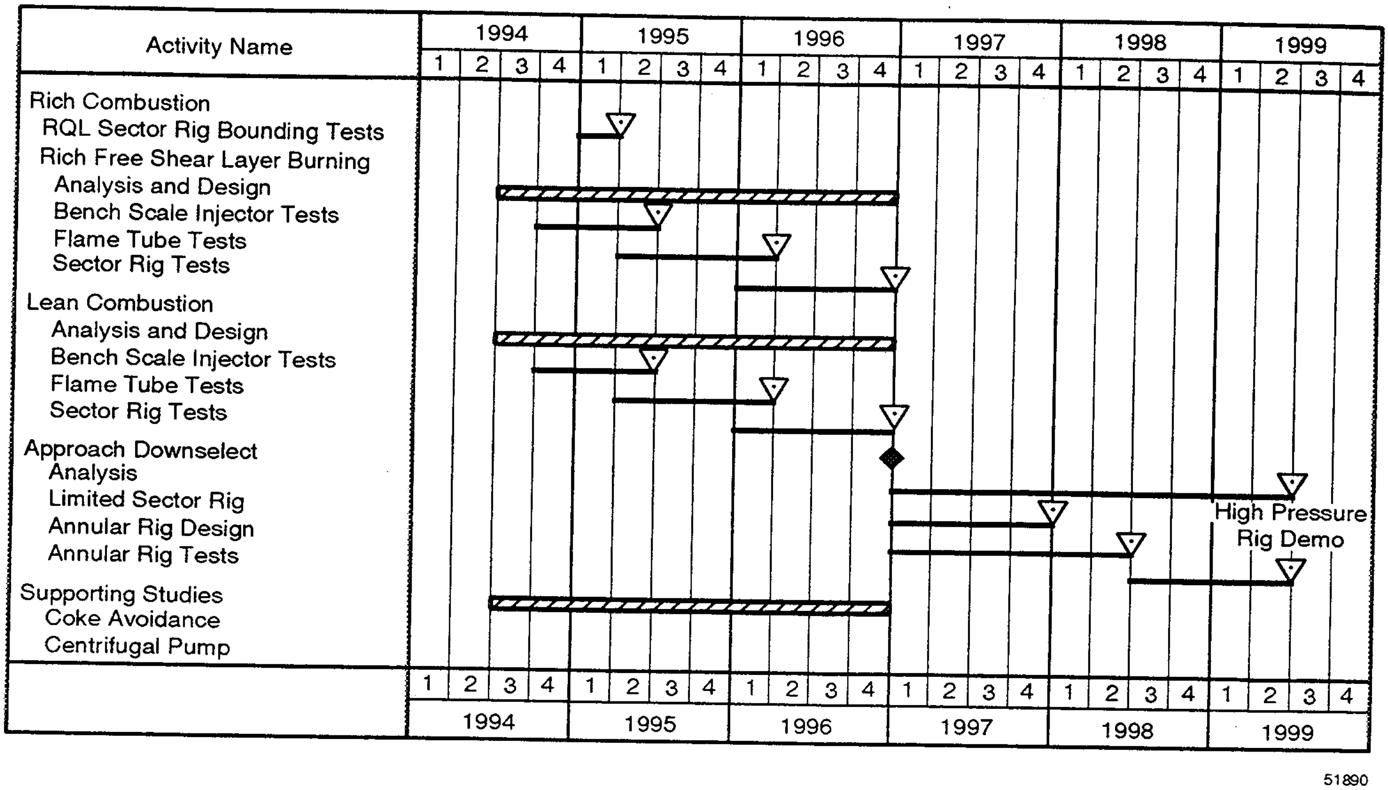


Figure 8–8. *Advanced Subsonic Technology Development Plan*

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13. ABSTRACT ***(Maximum 200 words)***

Recent advances in commercial and military aircraft gas turbines have yielded significant improvements in fuel efficiency and thrust-to-weight ratio, due in large part to increased combustor operating pressures and temperatures. However, the higher operating conditions have increased the emission of oxides of nitrogen (NOx), which is a pollutant with adverse impact on the atmosphere and environment. Since commercial and military aircraft are the only important direct source of NOx emissions at high altitudes, there is a growing consensus that considerably more stringent limits on NOx emissions will be required in the future for all aircraft. In fact, the regulatory communities have recently agreed to reduce NOx limits by 20 percent from current requirements effective in 1996. Further reductions at low altitude, together with introduction of limits on NOx at altitude, are virtual certainties. In addition, the U.S. Government recently conducted hearings on the introduction of federal fees on the local emission of pollutants from all sources, including aircraft. While no action was taken regarding aircraft in this instance, the threat of future action clearly remains. In these times of intense and growing international competition, the U.S. lead in aerospace can only be maintained through a clear technological dominance that leads to a product line of maximum value to the global airline customer. Development of a very low NOx combustor will be essential to meet the future needs of both the commercial and military transport markets, if additional economic burdens and/or operational restrictions are to be avoided. In this report, Pratt & Whitney (P&W) presents the study results with the following specific objectives: Development of low-emissions combustor technologies for advances engines that will enter into service circa 2005, while producing a goal of 70 percent lower NOx emissions, compared to 1996 regulatory levels. Identification of solution approaches to barriers to the productization and economic viability of the low-emissions technologies. Preparation of these technologies to facilitate an annular rig high-pressure demonstration.

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