



**an ASME
publication**

Copyright © 1979 by ASME

**\$3.00 PER COPY
\$1.50 TO ASME MEMBERS**



-1 JUL 1979
-1 JUN 1996

The Society shall not be responsible for statements or opinions advanced in papers or in discussion at meetings of the Society or of its Divisions or Sections, or printed in its publications. Discussion is printed only if the paper is published in an ASME journal or Proceedings. Released for general publication upon presentation. Full credit should be given to ASME, the Technical Division, and the author(s).

A Partial Oxidation Staging Concept for Gas Turbines Using Broadened Specification Fuels

R. M. CLAYTON

Jet Propulsion Laboratory,
California Institute of Technology,
Pasadena, Calif.

A concept is described for using a very fuel-rich partial oxidation process as the first stage of a two-stage combustion system for onboard processing of broadened specification fuels to improve their combustion characteristics. Results of an initial step in the experimental verification of the concept are presented, where the basic benefits of H₂ enrichment are shown to provide extended lean-combustion limits and permit simultaneous achievement of ultralow levels of NO_x, CO, and HC emissions. The H₂ required to obtain these results is within the range available from a partial oxidation precombustion stage. Operation of a catalytic partial oxidation reactor using a conventional aviation turbine fuel (JP5) and an unconventional fuel (blend of JP5/xylene) is shown to produce a "fuel gas" stream with a near-theoretical equilibrium H₂ content. However, a number of design considerations indicate that the precombustion stage should be incorporated as a thermal reaction.

Contributed by the Gas Turbine Division of The American Society of Mechanical Engineers for presentation at the Gas Turbine Conference & Exhibit & Solar Energy Conference, San Diego, California, March 12-15, 1979. Manuscript received at ASME Headquarters January 4, 1979.

Copies will be available until December 1, 1979.

A Partial Oxidation Staging Concept for Gas Turbines Using Broadened Specification Fuels

R. M. CLAYTON

ABSTRACT

A concept is described for using a very fuel-rich partial oxidation process as the first stage of a two-stage combustion system for onboard processing of broadened specification fuels to improve their combustion characteristics. Results of an initial step in the experimental verification of the concept are presented, where the basic benefits of H_2 enrichment are shown to provide extended lean-combustion limits and permit simultaneous achievement of ultralow levels of NO_x , CO and HC emissions. The H_2 required to obtain these results is within the range available from a partial oxidation precombustion stage. Operation of a catalytic partial oxidation reactor using a conventional aviation turbine fuel (JP5) and an unconventional fuel (blend of JP5/xylene) is shown to produce a "fuel gas" stream with near-theoretical equilibrium H_2 content. However, a number of design considerations indicate that the precombustion stage should be incorporated as a thermal reaction.

INTRODUCTION

Recent large price increases for aircraft turbine engine fuels and possible future fuel shortages have led to increased interest in widening the spectrum of fuels (including those from coal and oil shale syn-crudes) acceptable for aviation turbine engine operation. It is expected that a broader spectrum of acceptable fuels would lead to substantial fuel cost savings in the total life cycle costs of operating these engines. However, it is also expected that the combustion behavior of these fuels, particularly regarding pollutant emissions, will be poorer because aromatics content will be greater, fuel-bound N_2 will be greater, and vaporization rates will be lower. Thus, development of new combustor design concepts is

warranted if low emission levels are to be retained with the relatively poorer fuels.

A potential means of accomplishing this is through onboard fuel processing which, in principle, has the effect of decoupling the properties of the raw turbine fuel from the main combustion processes of the engine. The process of present interest is partial oxidation where a large portion of the fuel (not necessarily all of the fuel) to the engine would be reacted with a small portion of the air to the engine in a precombustion stage of an overall two-stage combustion system. Such a processing stage would generate H_2 -bearing gaseous products whose composition is dependent on the fuel richness of the reaction and on the hydrogen content of the fuel.

The notion of staged combustion for turbine engines is not new (1), but an objective of maximizing H_2 generation in the precombustion stage for the purpose of emission control is believed to distinguish this scheme from others. Reference (2) reports a similar scheme applied to an atmospheric pressure burner.

With fuels having hydrogen-to-carbon ratios of approximately 1.9, air-to-fuel ratios in the range of 5-6 theoretically produce a gas stream consisting of over 20% by volume of both H_2 and CO, the remainder of the products consisting mainly of H_2O . A "fuel gas" of this composition exhibits combustion characteristics superior to those of the initial raw hydrocarbon fuel by virtue of (a) its H_2 content, which provides a reduced lean flammability limit, broadening the margin between the leanness required for control of thermally generated NO_x and that providing adequate flame stability; and (b) its fully gaseous state, which provides the potential for richer mixing and combustion rates, as well as reduced thermal radiation to the combustor walls. Moreover, experimental results

reported in (1) suggest the potential of well pre-mixed, very fuel-rich reactions ($A/F < 7$) for suppressing the formation of intermediate nitrogen compounds (HCN , NH_3 , etc.) which are involved in the formation of NO from fuel-bound N_2 . Thus, processing a substantial portion of fuel (containing fuel-bound N_2) through a precombustion stage may also inhibit the production of fuel-generated NO_x during the final combustion stage.

It is envisioned that ultimately this processing stage could be physically integrated with the combustor. The partial-oxidation products would then be directed into the combustor where they would be mixed with additional air, and any remaining fuel, and burned in the combustor.

This paper summarizes the most current results from an ongoing experimental program to establish the practical feasibility of the concept. Ultralow levels of emissions have been adopted as targets. These targets are, in terms of emission index (g pollutant species/kg total fuel), 1.0 for NO_x and CO , and 0.5 for HC . The experiments are conducted using combustor inlet air state conditions typical of high-performance turbofan aviation engines.

The work has proceeded from using neat H_2 (bottled H_2 source)/JP5 admixtures to establish the basic benefits of H_2 enrichment, to the use of a simulated, partial-oxidation product gas mixture (also from a bottled source) substituted for the neat H_2 . This step is incomplete but is being undertaken as an expedient means of achieving a timely verification that the benefits of neat H_2 will be retained. It is necessary because a very fuel-rich precombustion reactor suitable for operation under gas turbine inlet air conditions is not yet available. In this regard, exploratory work has been done with a catalytic reactor. Demonstration of an integrated two-stage combustion system is a future goal of the work.

A description of the concept and progress toward its experimental verification is presented.

THEORETICAL CONSIDERATIONS

Partial Oxidation Products

Although the partial-oxidation process can be carried out either thermally or catalytically, the theoretical, adiabatic, equilibrium composition of the product gases are identical for the same initial reaction conditions. Details of the paths of the combustion chemistry for either reaction scheme are complex and not fully understood and their discussion is beyond the scope of this paper. Suffice to say that the overall process occurs with an excess of fuel and that the consumption of the available oxygen by a portion of the fuel provides heat, CO_2 , and H_2O that react with the remainder of the fuel to produce a final product gas whose composition is a function of the particular fuel stock and the reaction mixture ratio.

Figure 1 shows the results of one-dimensional, equilibrium-thermochemical calculations giving product composition (molar basis) and temperatures for a typical conventional turbine fuel with a hydrogen-to-carbon ratio of 1.92, over a range of fuel-rich air-to-fuel ratios and at an operating condition in the range of interest to the present work (nitrogen concentrations are not shown). The calculations were made using the computer program described in (3).

Note that solid carbon (C_s) is predicted with A/F ratios less than about 5.2 and that the product gas temperature increases rapidly at A/F ratios greater than 5.2. Carbon monoxide, one of the two major combustibles in the product gas, reaches a peak at

about this A/F ratio, whereas the other major combustible, H_2 , shows an increasing volumetric concentration in the A/F region of C_s formation. However, in terms of the mass of H_2 produced per unit mass of hydrocarbon fuel, it can be shown that H_2 mass productivity of the fuel also peaks at about the A/F ratio of 5.2, as illustrated in Fig. 2.

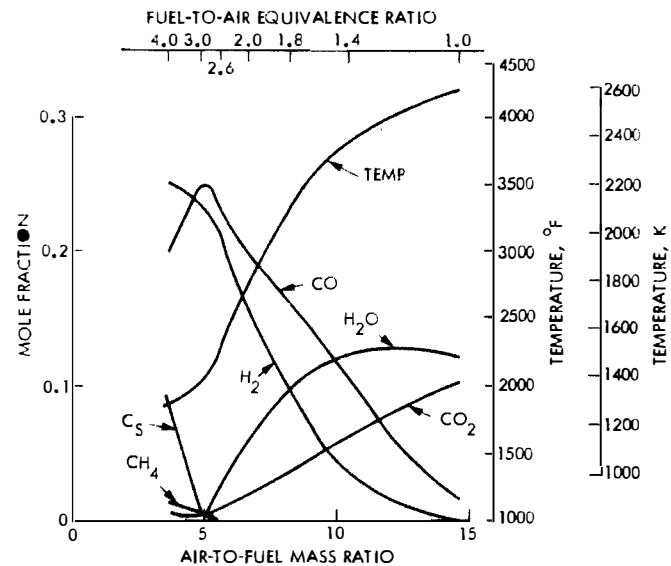


Fig. 1 Theoretical equilibrium composition and temperature of fuel-rich products for inlet air at 778 K (940°F) and $25.3 \times 10^5 \text{ N/m}^2$ (25 atm); fuel $\text{H/C} = 1.92$

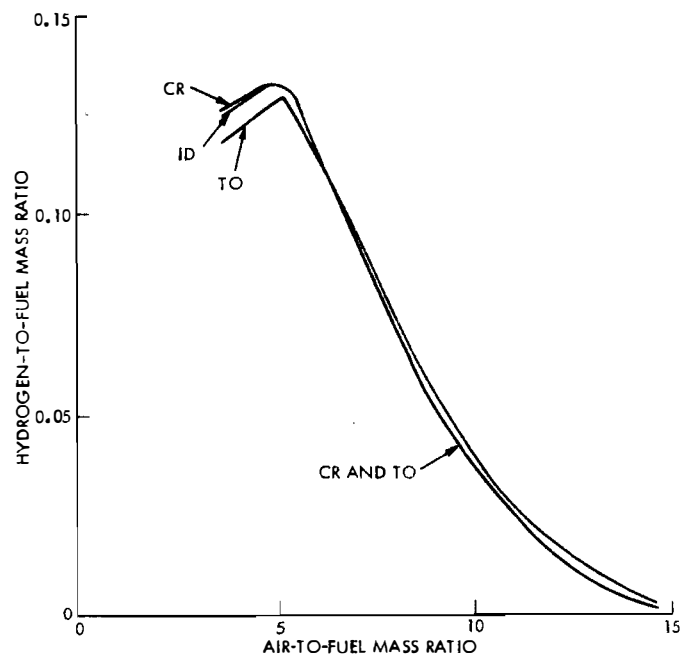


Fig. 2 Theoretical hydrogen-to-fuel mass ratio for various inlet air conditions typical for gas turbines: (TO) 778 K (940°F), $25.3 \times 10^5 \text{ N/m}^2$ (25 atm); (CR) 717 K (830°F), $8.1 \times 10^5 \text{ N/m}^2$ (8 atm); (ID) 422 K (300°F), $3.0 \times 10^5 \text{ N/m}^2$ (3 atm); fuel $\text{H/C} = 1.92$

Thus, from a theoretical standpoint, the optimal A/F ratio for sootless H₂ production is about 5.2, where the H₂ content of the product gas is about 6% of the mass of the combustibles in the gas. The lean flammability limit of the total product gas when mixed with additional air is estimated to occur at an overall A/F ratio of about 57 based on the procedure for fuel gas mixtures (at ambient temperature) outlined in (4), taking the H₂, CO, and CH₄ as combustibles and the H₂O, CO₂, and N₂ as inerts. The substantially reduced A/F lean limit of 57 for the product gas compared to about 24 for turbine fuels is of course the central argument for the subject concept.

Integrated Combustion System

Assuming that the technology for providing an optimized partial-oxidation reactor existed, integrating it into a two-stage combustion system has a substantial impact on present combustor design practices. However, a rudimentary conceptual design analysis serves to outline projected operational requirements and identifies potential design options that could accommodate the broad combustion range needed for aviation gas turbine engines.

A two-stage combustion system is depicted schematically in Fig. 3, where the various fuel and air flows are also identified. It is assumed that the precombustion stage is to be operated at its optimal A/F ratio of 5.2. The basic operational and control consideration is how the total system flows should be split between the two stages. For present purposes, the fuel and air splits are defined as $\dot{m}_{fg}/\dot{m}_{ft}$ and $\dot{m}_{ag}/\dot{m}_{at}$, respectively. From these definitions and the constant mixture ratio constraint for the first stage, it can be shown that the required fuel split to the first stage is related to the overall system A/F equivalence ratio (based on $\dot{m}_{ft}/\dot{m}_{at}$) as shown by the straight lines and the right-hand ordinate in Fig. 4. Each line represents an arbitrarily selected constant value of air split to the first stage. For a particular total air flow to the combustion system (i.e., a particular engine power level), each of these lines also represents a constant total throughput for the precombustion stage.

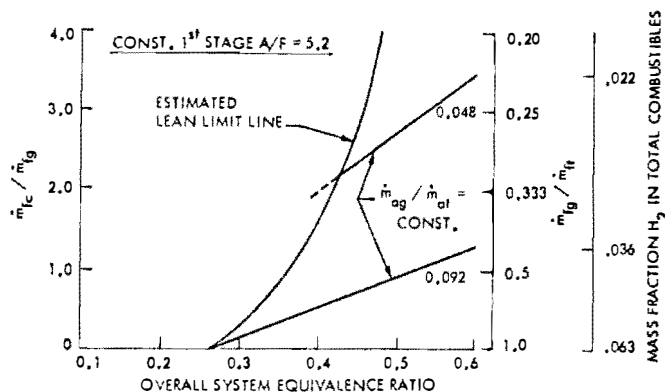


Fig. 4 Conceptual operating map for two-stage combustion system

If all the system fuel is directed through the first stage, then operation of the combustion system lies along the abscissa and the air split no longer can remain constant. The required air split for all fuel through the first stage is shown as a function of system equivalence ratio in Fig. 5.

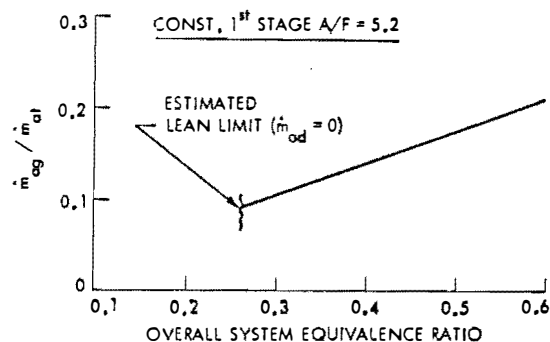


Fig. 5 Variation of air split for all fuel through the first stage

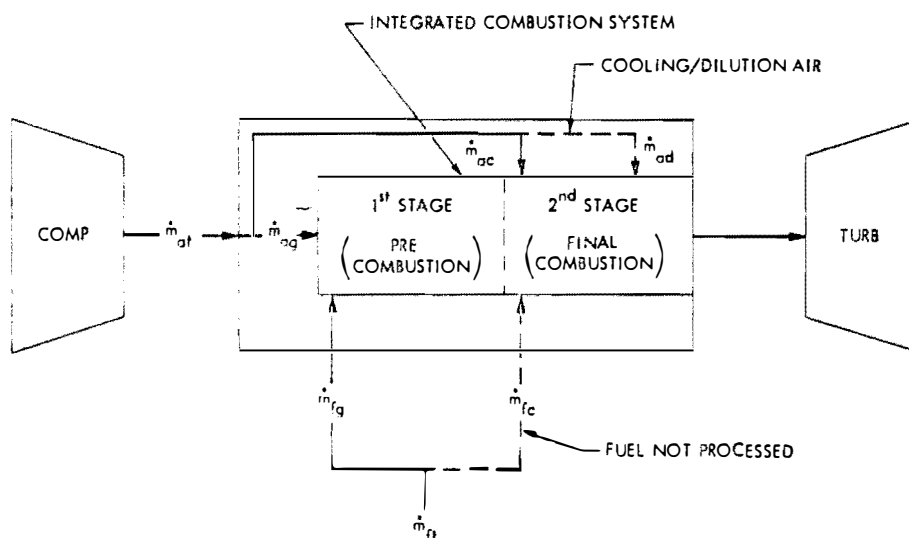


Fig. 3 Schematic of two-stage combustion system

The curved line shown on Fig. 4 is an estimated lean limit line based on considering the first-stage product gas stream as a fuel gas mixture having a composition and lean limit specified from the theoretical calculations discussed above. When all the raw fuel is processed through the first stage, this fuel gas mixture is the only "fuel" burned in the second stage; therefore, the system lean flammability limit is at its minimum value. When lesser amounts of raw fuel are processed (fuel split ratios < 1.0), the system lean limit increases by virtue of the increased limit of the raw fuel that bypasses the first stage and enters the combustion process in the second stage without prior processing.

The lean limit line represents a theoretical combustion limit, but not necessarily a lean blowout limit, since blowout is also a function of flame stabilization technique and reactant premixedness. Nevertheless, all other combustor factors fixed, fuels or fuel mixes with substantially lower flammability limits can be expected to provide substantially leaner blowout limits.

If the final combustion is to be carried out totally premixed with all the air to the second stage ($\dot{m}_{ad} = 0$), then only the system equivalence ratio region to the right of the limit line, shown in Fig. 4, is theoretically viable for completing the combustion reaction started in the precombustion stage. If a portion of the total air flow is to be used for film-cooling and dilution ($\dot{m}_{ad} > 0$), as would be required for an engine combustor, the final combustion reaction would necessarily be richer and the overall equivalence ratio could lie to the left of the limit line so long as the final reaction equivalence ratio was to the right of the limit line. In that case, the final reaction equivalence ratio depends on the fraction of the total system air used for cooling and dilution and on the overall equivalence ratio required for a particular engine operating condition. An evaluation of this relationship is shown in Fig. 6 for overall equivalence ratios of 0.30, 0.25, and 0.15, which are typical for maximum, cruise, and idle power, respectively. For all fuel through the first stage, air fractions of 0.45 or greater would keep the final reaction equivalence ratio above the lean limit for all power conditions.

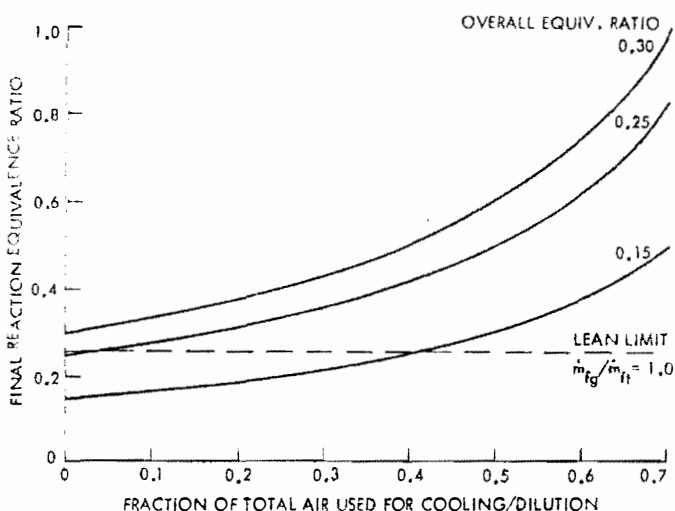


Fig. 6 Variation of final reaction equivalence ratio with air used for cooling and dilution

From the foregoing discussion and a further inspection of Fig. 4, four distinct schemes for system operation can be defined and are shown in Table 1.

Scheme 1 would provide the greatest benefit for application to broadened specification fuels. But scheme 2 might also be used depending on how poor the fuel is and whether processing only a portion of it would be adequate. Scheme 2 would be simpler to implement because variable fuel split control is probably easier than variable air split control, although compressor bleed might also be needed at low power to throttle system air mass flow while maintaining combustion stability.

PROGRESS IN EXPERIMENTAL VERIFICATION

The Benefits of H_2 Enrichment

It was deemed important to establish the basic benefits of H_2 enrichment as the first step in the overall process of experimentally verifying the utility of the two-stage combustion concept¹. The rationale for expecting significant combustion enhancement with admixtures of H_2 and jet fuel is described in (5) and (6) along with interim experimental results. These results showed that the targeted ultralow emission levels could be achieved simultaneously, but that the proportion of H_2 required (10-12 mass % in the total fuel) was greater than the maximum theoretically available from a partial oxidation precombustion stage ($\sim 6\%$). It was concluded from those results that improved premixing (H_2 , jet fuel, and air) was necessary to decrease the H_2 requirement.

Subsequent modifications to the fuel injector and flameholder for the JPL MOD 2 burner resulted in the version shown schematically in Fig. 7. Pertinent design parameters are summarized in Table 2. Although the burner was not intended to be a scale version of the G.E. CF6-50 combustor, analogous design parameters for a production version are shown for reference. The experimental burner has about 4% of the mass throughput and about 40% of the combustion space rate of the engine combustor.

For testing, the burner is housed within a heavy-walled pressure vessel which also serves as a plenum chamber for a preheated inlet-air supply. (See (6) for a description of the test facility.) The burner is designed to utilize 100% of the air flow in the combustion process; thus air film cooling and air dilution, which are normally used in an engine combustor, are omitted. In this way, combustion effects from air injection are avoided for the concept evaluation. The cylindrical combustion chamber is water-cooled, as are the inlet/flameholder assembly, sonic exhaust nozzle, and gas sample probe.

The burner is intended to operate with a near-homogeneous fuel/air mixtures. This is accomplished in the mixing duct, where gaseous H_2 , finely atomized jet fuel, and the air are combined. The interfacial component between the combustion and premixing zones is an axisymmetric, combination step/bluff-body flameholder. A torch igniter provides ignition but is inactive once steady burning is obtained.

¹Hydrogen enrichment of jet fuel can be considered to be a combustion enhancement scheme distinct from the two-stage combustion concept if the H_2 is available as a second fuel.

²It was expected that a similar H_2 proportion of the total combustibles would be required to achieve similar suppression of flammability limits regardless of the proportion of CO and jet fuel, since CO and jet fuel have similar lean flammability limits on an equivalence ratio basis.

Table 1. Comparison of two-stage operational schemes

Operational scheme	Air split	Fuel split	Advantage
1. All fuel through first stage	Variable	Constant @ 100%	Greatest benefit for alternate fuels
2. Constant air split to first stage	Constant	Variable	Simpler control
3. Parallel the lean limit line	Variable	Variable	None
4. Constant fuel split to first stage (<100%)	Variable	Constant	None

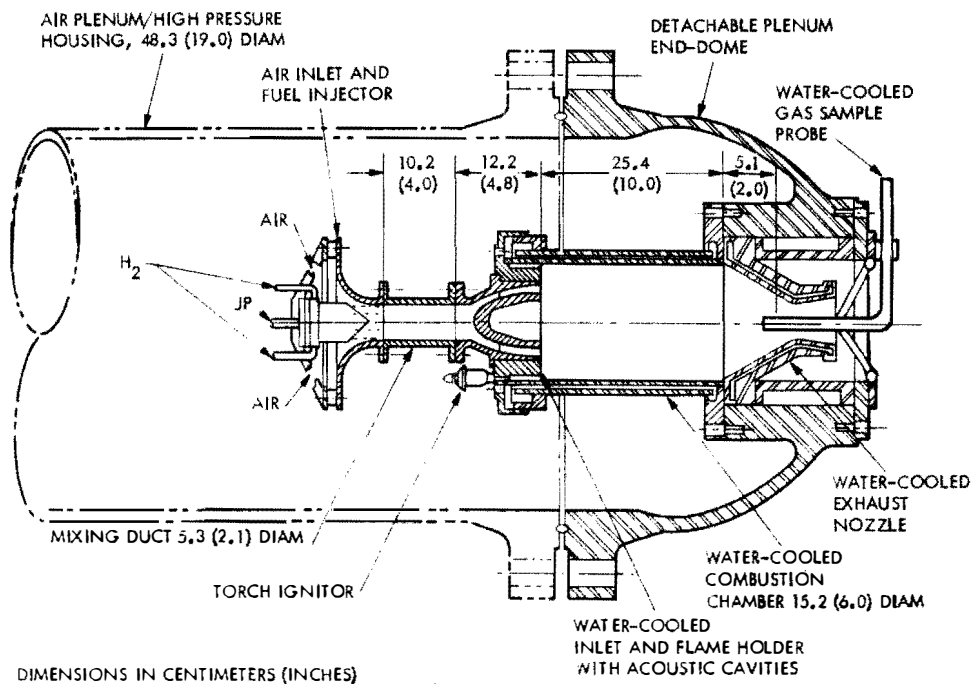


Fig. 1. MOD 2 research combustor installed in burner housing

Table 2. JPL Mod 2 burner design specifications and comparison with typical production engine burner^a

Specification item	Mod 2 burner ^b	Engine burner ^b
Air total pressure	$30.39 \times 10^5 \text{ N/m}^2$ (30 atm)	$30.39 \times 10^5 \text{ N/m}^2$ (30 atm)
Air total temperature	812 K (1460 R)	821 K (1477 R)
Air flow rate	4.6 kg/s (10 lbm/s)	103.4 kg/s (228 lbm/s)
Chamber reference velocity	18.3 m/s (60 ft/s)	25.9 m/s (85 ft/s)
Chamber dwell time (no recirculation)	5.0 ms	2.6 ms
Chamber L/D (shape)	1.7 (cylindrical)	3.0 (annular)
Combustion length	30.5 cm (12.0 in.)	34.8 cm (13.7 in.)
Combustion space rate ^c	$0.88 \times 10^6 \text{ J/hr-m}^3\text{-N/m}^2$ ($2.4 \times 10^6 \text{ Btu/hr-ft}^3\text{-atm}$)	$2.2 \times 10^6 \text{ J/hr-m}^3\text{-N/m}^2$ $5.9 \times 10^6 \text{ Btu/hr-ft}^3\text{-atm}$
Combustion equivalence ratio	$\text{LBO} < \text{ER} < 1.0$	> 1.0
Overall equivalence ratio	$\text{LBO} < \text{ER} < 1.0$	0.34
Air split for cooling	N.A.	30%
Air split for dilution	N.A.	38%
Premix reference velocity	157.8 m/s (518 ft/s)	N.A.
Premix Mach number	0.28	N.A (0.27 at compressor discharge)
Premix dwell time	1.4 ms	N.A.
Premix length	22.3 cm (8.8 in.)	N.A.

^aG.E. CF6-50. Data from (8):

^bTakeoff conditions.

^cAt overall equivalence ratio = 0.34.

Fuel Injection/Premix Section. As is seen from Fig. 7, premixing is carried out via a coaxial flow scheme where the fuels are injected at the bell-mouthed entry to a 5.22-cm (2.07-in.) diameter straight cylindrical duct, 10.16 cm (4.0 in.) long. The flow area provides a space velocity of about 140 m/s (460 ft/s) for the cruise power condition. This results in a residence time in the premixing section of about 1.6 ms.

The fuel injector is a JPL-fabricated device designed to inject liquid jet fuel and gaseous H₂ into the air stream from 15 pairs of coaxial tubes arranged to provide a near-uniform initial distribution of flow over the cross section of the mixing duct. The exit end of each pair of injector tubes is located approximately at the throat station of the bell-mouthed entry. This positioning of the injection tube ends,

combined with an appropriate location of the conical surface of the injector body, provides an arrangement where the fuels are injected into a region of near-axial air flow. Turbulence and recirculating flows are thus deliberately avoided in the mixing duct in order to reduce flame holding tendencies under the high temperature and pressure of the inlet air.

Atomization of the liquid fuel streams is accomplished by reversing the usual scheme for pressure atomizers where high-velocity fuel is injected into low-velocity air. In the present scheme, advantage is taken of the high-velocity air which is required for short premix residence times, and the fuel is injected at low velocities: of the order of 3 m/s (10 ft/s). Thus a large velocity gradient is available for fuel atomization. The coaxial arrangement of the injected flows also assures that the initial fuel distribution

will be insensitive to variations in all flow rates as operating conditions are varied.

Combustion Chamber Inlet/Flameholder Assembly.

The design criteria adopted for the combination step/bluff-body flameholder were to keep the mixture velocity through the annular flow area around the 7.6-cm (3.0-in.) diameter, semi-ellipsoidal centerbody equal to the approach velocity from the mixing duct, and to direct the mixture flow so as to establish roughly equivalent flameholding recirculation zones behind the annular step and the centerbody. Thus the premixed reactants are introduced to the combustion zone as an axially directed annular jet with velocities of the order of 140 m/s (460 ft/s), which provides adequate resistance to flashback yet imposes no more than a reasonable (for concept evaluation) 7-8% total pressure loss. Communication between the inner and outer flameholding zones is provided in the wake region behind four 1.27-cm (0.5-in.) wide struts that support the centerbody.

The centerbody and struts are water-cooled over the last 1.27-cm (0.5-in.) of length at the chamber end. The cavity in the centerbody serves to reduce heat transfer rates to the uncooled portion. The downstream face of the step portion of the inlet assembly is also water-cooled.

Acoustic cavities of quarter-wave slot configuration are positioned around the periphery of the inlet section, adjacent to the chamber wall. Half of them are sized for the first tangential acoustic mode frequency of the chamber and the other half tuned for the second tangential mode. This cavity design was found to be adequate to control high-frequency (3-5 KHz) combustion resonance.

Results. Salient emission results for this burner are shown for a typical cruise-power operating condition in Figs. 8-10 where it can be seen that:

- (1) The ultralow emission goals are simultaneously achieved or bettered over an equivalence ratio (based on H₂ + Jet fuel) range of 0.45 to 0.52 using 4.7-5.7 mass % H₂ (H₂ in total fuel.)
- (2) The lean blowout limit (LBO) is reduced from an equivalence ratio of 0.44 for Jet-fuel-only to 0.39 with 5.5% H₂.

These data also show that the target emissions are simultaneously achievable with JP5 alone in the 0.48 to 0.55 equivalence ratio range with the good premixing obtained with the current injection/mixing configuration. However, the high level of mixedness produces a high LBO (LBO ~ 0.44), and the HC and CO levels are very sensitive to equivalence ratio as LBO is approached. Addition of the relatively small amounts of H₂ used here broadens the margin between acceptable blowout stability and acceptable emission levels. This broadened margin would be highly significant in a full-scale premixed combustor where gross fuel and air maldistributions exist.

The 4.7-5.7% H₂ used to obtain these results represents better than a 50% reduction in required H₂ from previous results (5), and is within the range theoretically available from a very fuel-rich precombustion stage.

Generating the H₂

A catalytic, partial-oxidation reactor, designated H₂ generator L, has been used to explore the potential utility of this scheme as a design concept for a precombustion stage (7). The generator was operated over the pressure range of 3.45 to 4.66 x 10⁵ N/m² (3.4 to 4.6 atm) and with inlet air temperatures of approximately 422 K (300°F). Total mass flow through the generator ranged from 15 to 26 x 10⁻³ kg/s (0.034 to 0.058 lbm/s). Aviation turbine fuel JP5 was used for the bulk of the experiments, but a blend of JP5 and xylene (C₈H₁₀) was also used to provide a fuel with a

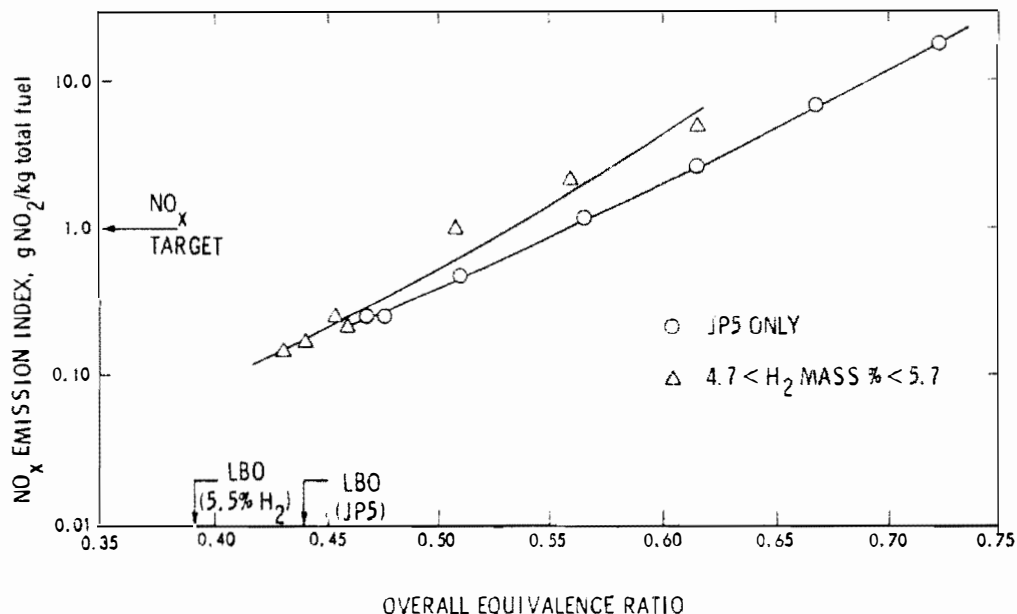


Fig. 8. NO_x emissions with and without hydrogen. Cruise power inlet air conditions: 723 K (660°F), 12.2 x 10⁵ N/m² (12 atm)

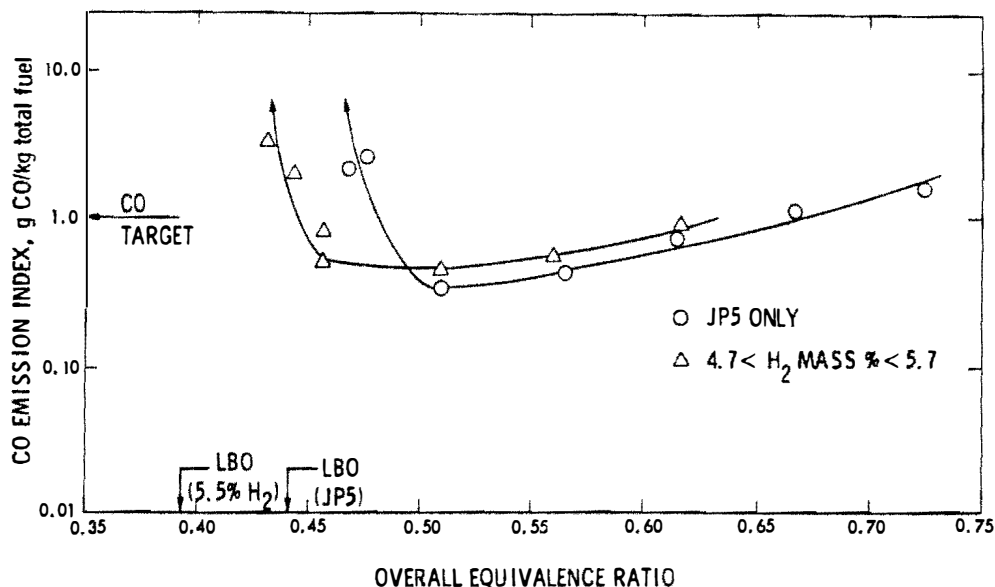


Fig. 9 CO emissions with and without hydrogen. Cruise power inlet air conditions; 728 K (850°F), $12.2 \times 10^5 \text{ N/m}^2$ (12 atm)

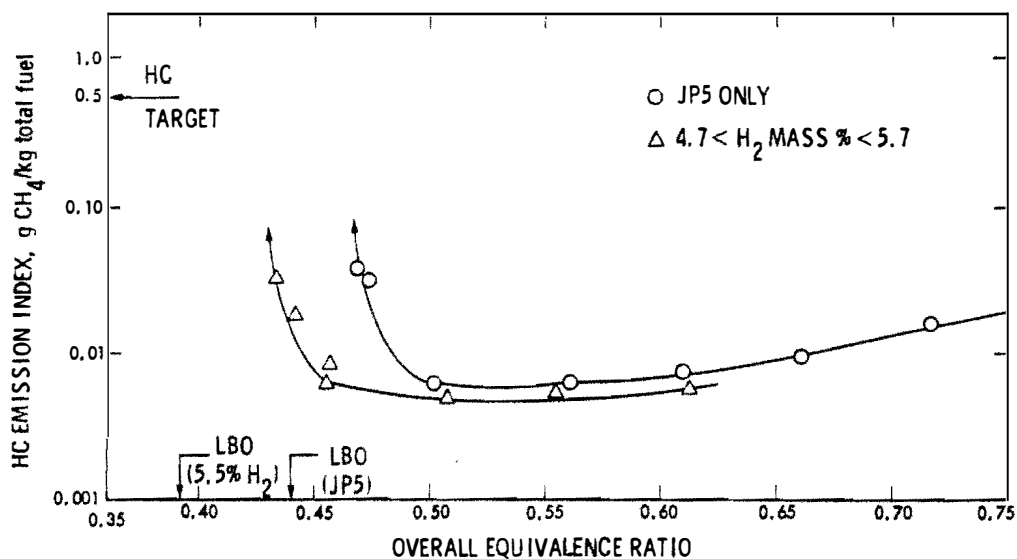


Fig. 10 HC emissions with and without hydrogen. Cruise power inlet air conditions; 728 K (850°F), $12.2 \times 10^5 \text{ N/m}^2$ (12 atm)

significantly increased aromatics content ($\sim 35\%$). In all experiments, the product gas was analyzed for its H_2 , CO, CO_2 , and CH_4 content.

Generator Description. Generator L is shown schematically in Fig. 11. Inlet air enters the ports (one or both, as controlled by external valves), is directed around the bed liner through the helical air passage and exits from the single port opposite the inlet ports. The purpose of the two inlet ports is to permit a variable amount of additional air preheat as the air absorbs the heat rejected by the bed. This preheat is greatest when all of the air enters the uppermost port, and least when all of the air enters the lower inlet port. In practice, the air is directed through the upper port for startup, and is changed to the lower port as the reaction stabilizes at a steady-

state condition. Further modulation of the air split was not used in these experiments.

After leaving the preheating passages, the air is mixed with fuel vapor (from an external vaporizer) in the induction passage and the fuel/air mixture is ducted to the generator inlet, where the mixture is diffused into the bed through an array of 18 holes in the wall of the induction tube. The fuel vapor is introduced into the air through an array of nine holes near the end of the fuel injection tube. Final mixture temperatures were generally in the range of 561–589 K (550–600°F).

The premixed fuel and air enter the bed at the conical transition section, which is filled with catalyst pellets, as is the cylindrical part of the generator. Reaction occurs throughout the bed and the resulting gaseous products are discharged through the duct at the top of the bed.

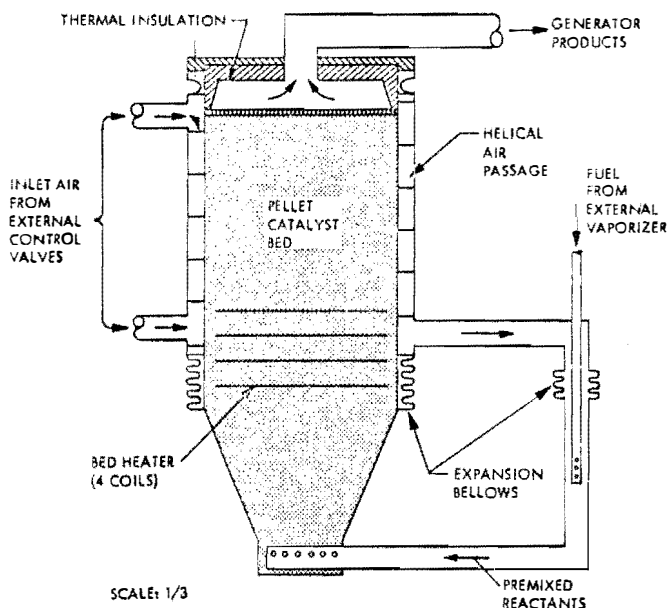


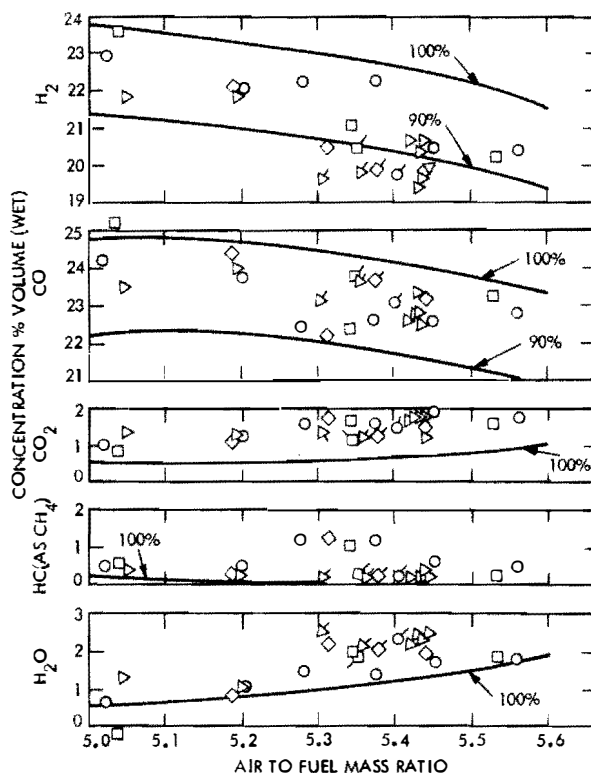
Fig. 11 Schematic of generator L

The catalyst used in all of the experiments is a pellet type, with pellets 6.4-mm (0.25-in.) diameter and 6.4-mm (0.25-in.) long. All catalyst material is manufactured by Girdler Division of Chemtron Corporation of Louisville, Kentucky. The bulk of the work was conducted using a catalyst loading consisting of a less reactive material in the conical section than for the cylindrical section of the generator. For this loading, approximately 1.18 kg (2.6 lbm) of G90B pellets were used in the conical section and 4.4 kg (9.7 lbm) of G90C pellets were loaded in the cylindrical section. These catalysts have 11 and 15% nickel by mass, respectively, and use an alumina substrate.

For startup, a portion of the catalyst bed is electrically preheated with a heating element composed of four coils of Inconel-sheathed, Nichrome wires as indicated in Fig. 11. The coils are supplied with a total of 1350 to 1600 kW of dc electrical power. This power range is adequate to heat the bed locally to 811 K (1000°F) in about 10 minutes.

Results. The concentrations of the four measured species in the product gas as a function of metered generator A/F ratio is shown for four levels of throughput and two fuels in Fig. 12. Concentrations are based on dry, soot-free volumetric concentrations using metered air flow rates and standard species balance procedures for estimation of water content. The estimated water concentrations are also shown in Fig. 12. The JP5/air theoretical equilibrium composition curves for $3.0 \times 10^5 \text{ N/m}^2$ (3 atm), 422 K (300°F) air are shown for reference. Theoretical calculations for the blended fuel were not made.

Considerable data scatter is apparent, but taken as whole, the data for JP5 follow the trends for H_2 yield expected from theoretical considerations, with the yield generally within 90% of theoretical. Some reduction in H_2 yield is apparent as the throughput was increased to the highest value tested. But whether this was the result of a true bed capacity limitation or the effects of soot deposition is uncertain. The highest throughput levels not only gave indication of high soot production, but also occurred late in the runs when accumulated deposits were probably already present.



\dot{m}_g , kg/s	lbm/s
○ 0.0154-0.0163	0.034-0.036
■ 0.0186-0.0191	0.041-0.042
◇ 0.0213-0.0218	0.047-0.048
▷ 0.0240-0.0268	0.053-0.059

OPEN - JP5
TAILS - BLEND
—— THEORY
(JP5/AIR)

Fig. 12 Product composition for generator L

The data for the run with the fuel blend show somewhat less H_2 yield than for the JP5 fuel, but this is expected since the hydrogen content of the blend is approximately 12.8% by mass compared to the nominal 13.3% for JP5.

The trend for CO yield was also consistent with the theoretical trend and was generally within 90% of theoretical equilibrium.

The concentrations of CO_2 and unconverted hydrocarbons (as CH_4) in the product gas stream were always somewhat greater than expected from theoretical considerations. This reflects the nonequilibrium performance of the generator that are apparent in the less than theoretical yield of H_2 and CO previously mentioned.

Since the H_2 content of the product gas is considered to be the most influential factor in the concept of improving the combustion properties of the raw fuel by onboard fuel processing, the quantity of H_2 produced per unit quantity of fuel (H/F) and the fraction of H_2 in the total combustibles are important indices of generator performance. Maximizing these

indices would provide the optimal application of the partial oxidation process to the two-stage concept for broadening acceptable fuel specifications. The H/F mass ratios and H_2 fraction in the combustibles observed in these tests are shown in Fig. 13, where they again compare favorably with theoretical equilibrium values. As did the volumetric H_2 yields, the H/F ratios for JP5 fuel generally fall within 90% of the theoretical values, with some reduction indicated for the higher throughput levels. The fuel blend, of course, exhibits a reduced H_2 mass production due to its smaller initial hydrogen content.

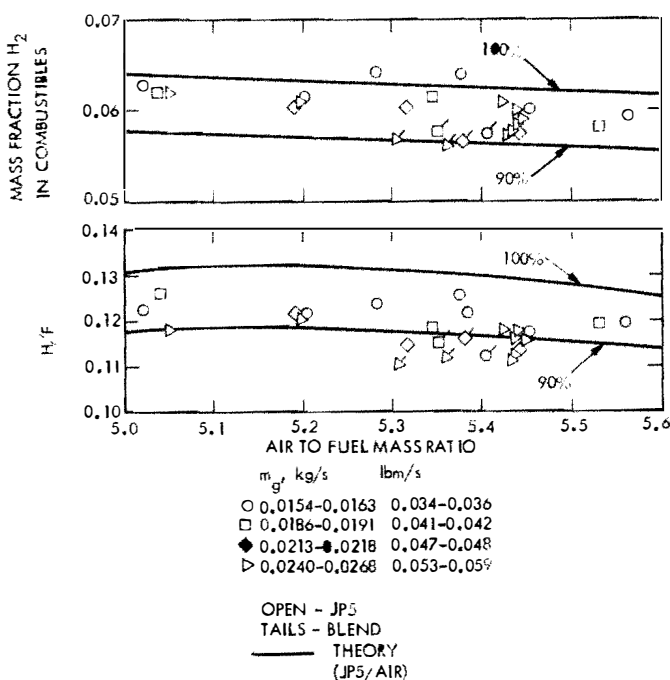


Fig. 13 Hydrogen yield indices for generator L

In summary, the fuel gas stream produced by the catalyzed partial oxidation process, and in particular by the generator tested, using a conventional and an unconventional turbine fuel, appears to be near the theoretical gaseous composition attainable. The utility of this fuel gas stream in application to a second stage of combustion in a continuous-flow, turbine-engine-like burner system of course remains to be demonstrated.

CONCLUDING REMARKS

A partial oxidation staging concept for gas turbine combustors using broadened specification fuels has been described and elements of its experimental verification have been presented. The concept is proposed as a means of controlling gaseous pollutant emissions to ultralow levels while maintaining acceptable lean blowout limits.

While the practical feasibility of the concept is as yet incompletely demonstrated due to the lack of a satisfactory partial oxidation reactor, the following conclusions can be stated from results to date.

- (1) Admixtures of H_2 and conventional JP5 jet fuel used in an experimental premix

combustor of quasi-prototype functional design provide a significant extension of the lean blowout limit.

- (2) The proportion of H_2 in the total combustibles required to achieve ultralow levels of emissions simultaneously with the extended lean limits is within the theoretical capabilities of a very fuel-rich partial oxidation process.
- (3) A catalytic process can produce near theoretical equilibrium products under very fuel-rich operating conditions, but considerations of simpler startup, greater durability, lack of abrasive particulates, and greater tolerance to soot production make thermal processes potentially more attractive.
- (4) Soot production is likely to be a persistent problem with very fuel-rich precombustion, especially with fuels with high aromatics content. However, unreported JPL results with rich thermal reactors indicate that sooting tendencies can be minimized by thorough premixing and high preheat.

ACKNOWLEDGMENTS

The author expresses appreciation to all individuals who have contributed to the progress of this investigation. Particular gratitude is due to Roy Bjorklund and Milton Noel, test engineers, Donald Cerini, principal designer and consultant for the catalytic H_2 generator, and Clarence Tuttle, engineering assistant and test facility operator.

This paper presents the results of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, for NASA under Contract NAS7-100, and for the Air Force Aero Propulsion Laboratory by agreement with NASA.

REFERENCES

- 1 Roffe, G., and Ferri, A., Pre vaporization and Premixing to Obtain Low Oxides of Nitrogen in Gas Turbine Combustors, NASA CR-2495, March 1975.
- 2 Yamagishi, K., et al., "A Study of NO_x Emission Characteristics in Two Stage Combustion," 15th Symposium (International) on Combustion, The Combustion Institute, 1975, pp. 1157-1166.
- 3 Gordon, S., and McBride, B. J., Computer Program for Calculation of Complex Chemical Equilibrium Compositions, Rocket Performance, Incident and Reflected Shocks, and Chapman-Jouguet Detonations, NASA SP-273, Lewis Research Center, Cleveland, Ohio, 1971.
- 4 Coward, H. F., and Jones, G. W., Limits of Flammability of Gases and Vapors, Bulletin 503, Bureau of Mines, Washington, D.C., 1952.
- 5 Clayton, R. M., "Hydrogen Enrichment for Low Emission Jet Combustion," Evaporation-Combustion of Fuels, Advances in Chemistry Series No. 166, American Chemical Society, 1978.
- 6 Clayton, R. M., Reduction of Gaseous Pollutant Emissions from Gas Turbine Combustors Using Hydrogen-Enriched Jet Fuel-A Progress Report, Technical Memorandum 33-790, Jet Propulsion Laboratory, Pasadena, California, October 1, 1976.
- 7 Clayton, R. M., Performance Evaluation of a Catalytic Partial Oxidation Hydrogen Generator Using Turbine Engine Fuels, AFAPL-TR-77-62, June 1977.
- 8 Rudey, R. A., Status of Technological Advancement for Reducing Aircraft Gas Turbine Engine Pollutant Emissions, NASA TMX-71846, Lewis Research Center, Cleveland, Ohio, December 1975.