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PHASE I - DESCRIPTION AND STATUS

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THE ADVANCED LOW-EMISSIONS CATALYTIC-COMBUSTOR PROGRAM

PHASE I - DESCRIPTION AND STATUS

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ABSTRACT

The Advanced Low-Emissions Catalytic-Combustor Program is an ongoing three-phase contract effort with the primary objective of evolving the technology required for incorporating catalytic combustors into advanced aircraft gas-turbine engines. Phase I is currently in progress. At the present time, analytical evaluation is being conducted on advanced catalytic-combustor concepts - including variable geometry - with their known inherent potential advantages of low-level pollutant emissions, widened combustion stability limits, and reduced pattern factor for longer turbine life. Phases II and III will consist of experimental evaluation of the most promising concepts.

INTRODUCTIC

This paper gives an overview of the ongoing Advanced Low-Emissions Catalytic-Combustor Program funded by NASA and the Air Force. NASA Lewis Research Center is administering the program. Program objectives, plan, schedule, pollution and performance goals, catalyst advantages, present problems, and the present status of identified combustor concepts will be discussed.

The possible increase in upper atmosphere oxides of nitrogen (NO_x) levels due to future aircraft number density increases had been predicted to adversely decrease ozone concentration levels (refs. 1 and 2). Recent studies (refs. 3 to 5) suggest such effects are less than previously estimated. However, all these studies indicate there still exist major uncertainties and gaps in our knowledge that preclude accurately forecasting the magnitude of these effects.

Consequently, the reduction of pollutant emission levels has been and still remains a desirable principal design goal for future-aircraft, gas-turbine engines.

Reduction of present NO_x emission levels for cruise and for landing-takeoff requires continual advances in combustion-system technology. The NASA Experimental Clean Combustor Program produced lower NO_x emission levels than exists for conventional combustor technology (refs. 6 and 7). But, to achieve a desirable lower level for NO_x emissions, a more advanced technology is needed. A technique for achieving low NO_x emission levels has been experimentally demonstrated with a lean, premixing-prevaporizing flame-tube combustor (ref. 8). The low-emission potential of this technique in practical combustor systems will be evaluated by NASA. Another technique demonstrated in a flame-tube combustor gave the promise of obtaining at least 60 percent lower NO_x emission levels. This technique utilized catalytic combustion of propane which gave a NO_x emission index of $0.06 \text{ g NO}_x/\text{kg fuel}$ at an inlet fuel-air mixture temperature of 800 K and at a pressure of 300 kPa (ref. 9).

The Advanced Low-Emissions Catalytic Combustor Program, to be discussed herein, will analytically and experimentally evaluate the known inherent advantages, to be discussed later, of catalytic combustion applied to advanced aircraft-combustor concepts (refs. 9 to 15). Results obtained will also have application to advance stationary ground power and alternative-fuels combustion technology.

PROGRAM DESCRIPTION

General

The Advanced Low-Emissions Catalytic-Combustor Program is a multiphase effort with the primary objective to analytically generate and to experimentally demonstrate the technology needed to develop catalytic combustors for reducing NO_x emission levels and for improving the performance of advanced subsonic aircraft during cruise operation as well as for meeting the U.S. Environmental Protection Agency (EPA) 1979 emission standards (ref. 16) for the landing-takeoff cycle of T-2 aircraft engines for altitudes less than 915 meters. T-2 class engines are defined by the EPA as all turbofan or turbojet engines, except the JT3D, JT8D, and supersonic transport engines having an equivalent power output equal to or greater than 35.59 kilonewtons-thrust.

This advanced combustor program will generate technology applicable to future, advanced technology engines with high overall compressor pressure ratios and with high turbine-inlet temperatures. Combustor-size constraint is guided by the NASA Energy Efficient Engine (E3) Program goals which are representative of a baseline for future, advanced technology engines.

Program Plan

The program is being conducted in three successive phases which are as follows:

Phase I: Design study. This phase consists of an analytical evaluation of several concepts for annular combustors using catalytic techniques. The most promising concepts will be selected to go into preliminary design. Phase I is a fifteen-month effort.

Phase II: Screening tests. This phase shall consist of a series of designs, tests, modifications and retests in a combustor sector rig to experimentally evaluate two combustors using catalytic techniques. Phase II shall be a twelve-month effort and be restricted to one of the Phase I Contractors.

Phase III: Combustor refinement. This phase shall consist of further refinement and testing in either a sector or annular combustor rig of one or two catalytic combustor designs for development of technology needed for aircraft application. Phase III shall be a twelve-month effort and be restricted to the Phase II Contractor.

Program Schedule

The program schedule plan is shown in table I. Phase I contracts were awarded in October 1977 to the General Electric Company and about two months later to the Pratt & Whitney Aircraft Company to independently generate and evaluate six catalytic combustor concepts. Two of the most promising concepts from each set of six will then go into preliminary design. The program manager at Pratt & Whitney Aircraft is Dr. G. Sturges and the principal investigator at General Electric is Mr. C. C. Gleason. Phase II will be awarded to one of the previously mentioned contractors in about mid-1979 to perform experimental screening tests on the two most promising designs selected from Phase I. Phase III is scheduled to be completed by the end of 1981.

Program Goals

The overall goal is to substantially reduce cruise NO_x emissions using catalytic combustion techniques that inherently have the potential for widening combustion stability limits and increasing turbine blade life with minimum compromises, if any, in durability and maintainability. Smoke emissions are not of primary interest in this program; however, smoke levels should meet the EPA standards.

Pollution goals. The gaseous pollutant emission goals are presented in table II. Criteria for selecting the optimistic goal for the NO_x emission level during normal subsonic cruise ($M = 0.85$; 1.07 km) was based upon the experimental, catalytic-combustor flame-tube results of reference 9. As shown in the table, current technology engines exceed the program goal by more than an order of magnitude. For altitudes less than 915 meters, the goal is to meet the 1979 EPA Standards. Values are stated in terms of emission index and the 1979 EPA parameter Standards. Emission index is the ratio of grams of pollutant formed per kilogram of fuel consumed. The EPA parameter represents the total pollutant mass emitted over the time of a standard landing-takeoff cycle that is normalized with thrust.

Performance goals. The key performance goals are shown in table III. These goals represent values to be met so catalytic-combustor performance will be equal or superior to that of near-term advanced aircraft-gas-turbine engines. Concepts selected for experimental testing and refinement should have a high development potential - minimum constraints for future implementation.

THE CATALYTIC COMBUSTOR

Advantages

Present day combustors with high heat-release rates have peak flame temperatures greater than 1900 K. As a result, high levels of NO_x emissions are present. The lean, premixing-prevaporizing technique previously mentioned has a low adiabatic flame temperature which prevents the formation of high levels of NO_x emissions. However, at the required low fuel-air ratios, flame instability and combustion efficiency are potential problems. These problems are circumvented by using the technique of heterogeneously-catalyzed combustion.

The advanced catalytic combustor shown schematically in figure 1 is now being recognized as a possible future replacement of conventional combustors. References 9 to 15 have pointed out the attractive and distinguishing features that make the catalytic combustor a viable candidate. Ultra-low thermal NO_x emission indices - 0.06 g NO_2 /kg fuel - are obtainable with high heat-release rates at relatively uniform temperatures (≈ 1300 K) well below the lean flammability limit. Combustion stability is far superior to other combustor types not only because homogeneous thermal combustion occurs in parallel with heterogeneous thermal reactions at the catalyst surface, but also because of the increased combustion-zone thermal inertia which damps system thermal perturbations. Homogeneous combustion is a result of the heterogeneous combustion temperature monotonically increasing along the axis of the catalyst to a value high enough to initiate reactions off the catalyst surface within the homogeneous fuel-air mixture at a temperature (≈ 1300 K) substantially less than required for conventional combustion. At this lower temperature level, the homogeneous gas-phase reactions control the energy release as the gas flows through the

catalyst. Consequently, the exit section of the catalytic combustor need not have any catalyst. Exit gas temperature level is approximately the adiabatic flame temperature and is essentially uniform across the catalyst exit plane; hence, an improved pattern factor. A nearly uniform catalyst exit temperature permits higher average exit temperatures without damage to turbine blades and gives a reduced specific fuel consumption. Finally, the monolithic-substrate structures for the catalyst do not present a major combustor-pressure-drop problem.

Current Disadvantages

Successful implementation of catalytic combustor systems into future aircraft will require further work for minimizing and/or eliminating the following present-day application constraints: (1) uniformity of inlet velocity, temperature, and fuel-air composition; (2) thermal durability and performance stability of the catalytic reactor over long time periods; and (3) autoignition and flashback.

A uniform inlet velocity profile to the catalytic reactor is highly desirable since the monolithic substrate will preserve the inlet velocity distortions to the catalyst exit plane. Temperature at the catalyst inlet plane should be practically uniform since combustion efficiency is dependent on the temperature level. Complete upstream fuel vaporization for uniform fuel-air composition is desirable, but may not be necessary. Good performance has been reported with 5 to 10 percent of the fuel not vaporized (ref. 12). Reference 15 suggests the volumetric expansion of reacting gases within each catalyst tube during homogeneous combustion helps prevent unvaporized fuel droplets from impinging on the catalyst tube wall. Nevertheless, uniformity of the inlet fuel-air mixture is desired to avoid the possibility of causing local high-temperature regions within the catalyst bed.

Thermal durability for continuous and cyclic operation without catalyst degradation is a cost-effective performance requirement. The maximum temperatures tolerated by present-day catalytic reactors is about 1650 K (table IV). A near term (2-3 yr) projection raises this temperature limit to 1700 K. Far term (5-10 yr) projection values exceed 1800 K assuming a major development effort (ref. 17). This catalytic-combustor technology program will use existing catalyst technology. Reactivity of the catalytic reactor must be acceptably stable at a high enough level for repeatable, reliable and rapid low-temperature ignition over a long-term operating period. More work needs to be done in this area.

Available autoignition data (ref. 18) for pressures up to sixty atmospheres shows an autoignition delay time of about 4 milliseconds for hot, sea-level takeoff conditions (fig. 2). If the catalytic combustor is to be used during sea-level takeoff operation, the length of the fuel-air mixing section can be at most only 12 centimeters for a 30 m/sec. reference velocity. Figure 3 shows the evaporation times for two different drop sizes of Jet A. Clearly, the fuel injector must finely atomize the fuel for rapid vaporization and mixing without autoignition. Flashback has been observed in a catalyst system with increases in the fuel-air ratio after very high combustion efficiency was obtained (ref. 13). An active flame formed immediately upstream of the catalytic reactor with subsequent flame propagation upstream to the fuel inlet. Flashback can be eliminated by designing for a higher velocity in the fuel-air inlet section. However, it must be recognized the magnitude

of the mixture velocity that can be used will be determined by the amount catalyst performance is degraded.

Catalyst Materials

Choices of catalytic reactor materials are being independently made by the two contractors for Phase I. General Electric has subcontracted with Engelhard Industries to furnish engineering support and to provide catalyst design and performance data. Pratt & Whitney Aircraft Company is working with the United Technology Research Center on the catalytic-reactor material selection, design, and performance.

Engelhard Industries conducted a test program (ref. 19) to evaluate two lengths - 10.2 and 12.7 cm - of their recommended catalyst reactor of type DXE-441. This reactor design consists of palladium impregnated into a stabilized alumina washcoat on a zircon composite honeycomb support. The honeycomb has 14.1 holes per square centimeter. Each hole has a hydraulic diameter of 0.1722 cm that gives 54.2 percent open area for the catalytic reactor. Test results (fig. 4) at a pressure level of 304 kPa show combustion efficiency dependent on overall fuel-air ratio for Jet-A at reference velocities of 21.3, 27.4, and 33.5 m/s. The inlet temperature of 633 K, inlet pressure of 304 kPa, and reference velocity of 21.3 m/s approximate minimum-cruise power level. As seen from figure 4, the longer 12.7 cm catalyst has a higher combustion efficiency (99 percent) over the range of inlet velocities and fuel-air ratios required. Minimum cruise and approach power fuel-air ratio is selected as 0.026 to insure the combustion efficiency is at least 99 percent. Consequently, the 12.7 cm length was selected for evaluating combustor concepts. Catalyst pressure loss (fig. 5) can be lowered by reducing the honeycomb substrate wall thickness which offsets the higher pressure drop of the longer length selected.

Zirconia has been selected by Pratt & Whitney Aircraft Company as the monolithic-substrate material to use in some of their concepts because it alone can be safely used at a temperature level of 1900 K. At high temperature, zirconia has very high thermal shock resistance, very high axial strength, and high transverse strength (ref. 20). Additional catalytic reactor material and design evaluation is an ongoing effort with the graded-cell reactor being seriously considered (ref. 21). It consists of three different cell-size catalyst elements placed in series. The graded-cell reactor studied (table V) contains large cells at the front of the bed for stability which then become smaller in the downstream axial direction by a series of two cell size step changes that help to maintain a high efficiency of conversion. A hexagonal cell shape was chosen to improve bed strength while permitting an increase in porosity. The first element in this three element catalytic reactor is similar to a W. R. Grace bed in Cordierite support material and the second element is similar to another W. R. Grace bed in Poramic support material (ref. 22). Reactor length is 16.5 cm for 100 percent combustion efficiency. For an adiabatic graded-cell reactor, the axial temperature distribution was determined (fig. 6) from the results of analyzing the data of reference 22. One result showed the normalized-local-temperature rise was only dependent on reference velocity when the adiabatic flame temperature of the fuel-air mixture exceeded 1250 K. Figure 6 shows the first and last 25 percent of the reactor length does not significantly contribute to the overall temperature rise at takeoff. Pressure loss calculations for all three elements in contact gave a 2.54 percent loss in total pressure

which exceeds the assigned allowable pressure loss of 1.65 percent. However, separation of the elements by two or three hydraulic diameters is predicted to give a lower total pressure loss. This gives the graded-cell reactor with separated elements a potentially significant pressure-loss advantage.

PHASE I STATUS

The objective of the concept analysis and evaluation portion of Phase I is to select the two most promising concepts from each set of six independently conceived by each of the two contractors. Each set of two concepts would then go into preliminary design. Due to an earlier contract award to General Electric Company, two of the six concepts have been identified and selected for preliminary design. Analysis and evaluation of the six concepts by Pratt & Whitney Aircraft Company is nearing completion. Brief descriptions of the two General Electric concepts and the Pratt & Whitney concepts under evaluation are presented below.

The two most promising General Electric concepts identified are shown in figure 7. Maximum fuel flow to the catalytic reactor will be restricted to maintain reactor temperature below 1811 K (table IV). Combustor liners downstream of the catalyst will be cooled by backside convection and have a 0.5 mm thick thermal barrier coating on the inside wall. This permits a maximum allowable catalyst-to-total fuel flow split of 0.92 at normal cruise. Both concepts are mechanically promising. The can-annular, reverse-flow concept has the best catalyst accessibility. Catalyst accessibility for the basic, parallel-staged concept is viewed as being a possible problem during testing and development, but not after a final configuration has been achieved. The normal-cruise NO_x emission index predicted for each of the concepts, as shown, is the low-level of two. Further reductions in the NO_x emission index possibly can be achieved by changing to a hot-liner wall for the pilot stage that will permit more airflow through the catalyst stage. As a result of the increased airflow, the fuel flow to the catalyst stage can be increased - maintaining a constant overall fuel-air ratio - with a corresponding decrease in fuel flow to the pilot stage. This decrease in fuel flow to the pilot stage with its relatively high NO_x -emission level helps reduce the overall NO_x -emission level from the combustor. Fuel to the catalyst stage for both concepts is introduced just below the approach power level (30 percent take-off power) while the pilot stage fuel flow is decreased to maintain a constant increase in combustor fuel flow. Pilot stage fuel flow is finally decreased to a maintenance level by fueling only a fraction of the pilot stage injectors. This fuel flow is held constant until the catalytic-reactor maximum use temperature level is reached. At this point, the pilot fuel flow is then increased.

The six concepts of Pratt & Whitney Aircraft Company are presently undergoing analysis and evaluation; therefore, complete concept details are not given, but only the descriptive combustor-concept names which are the following: (1) basic, pure catalytic reactor; (2) rich, front-end hybrid; (3) basic radially-staged; (4) axial fuel-staging with variable geometry; (5) radially-staged, can-annular with variable geometry; and (6) folded Vorbix with a radial inflow pilot and individual cruise catalytic combustor.

CONCLUDING REMARKS

Phase I is currently about 60 percent completed. Two sets of six catalytic-combustor concepts each have been identified with two of the most promising concepts selected from only one of the two sets. The two most promising concepts from the remaining set-of-six should be selected by December. Preliminary detailed design work for the total of four-most-promising catalytic-combustor concepts should be completed in January 1979.

Results to date from the two independent approaches used in the Advanced Low-Emissions Catalytic-Combustor Program have shown catalytic reactors can be incorporated as a series or parallel staged elements within combustor configuration concepts approaching the E^3 baseline design which is taken to be typical for advanced technology engines. Also, these studies have shown catalytic combustors have the potential for operating over the EPA LTO cycle and at cruise with a high combustion efficiency and at a very low emission level of pollutants. However, if very low emission levels of pollutants, widened combustion stability limits, and extended turbine blade life are to be realized from a practical, full-size annular catalytic combustor, then a greater technology evolution will be needed in raising the monolithic-substrate temperature limits, improving substrate-support techniques, and in generating thermal-fatigue resistant catalyst-cell-structure designs. Achievement of further advances in catalytic-combustor technology will be obtained by a careful attention to details for the catalytic-reactor material development and design as well as for the upstream fuel-air preparation section internal fluid dynamics. Proper designs for the fuel-air preparation section will minimize or eliminate the occurrence of autoignition, flashback, and high-temperature streaking within the catalytic reactor. Phases II and III will experimentally test and refine the selected catalytic-combustor designs built from the Phase I most promising concepts.

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TABLE I. - SCHEDULE FOR ADVANCED LOW EMISSIONS

CATALYTIC COMBUSTOR PROGRAM CALENDAR YEARS

Contract effort	1977	1978	1979	1980	1981
Phase I GE P&W (Design study)					
Phase II (Screening tests)					
Phase III (Combustor refinement)					

TABLE II. - POLLUTION LEVELS AND GOALS

Parameter	Combustor pollutant			Current cruise NO _x emissions
	Oxides of nitrogen	Carbon monoxide	Unburned hydro- carbons	
Cruise- emission index, g NO ₂ /kg fuel	1 ^a	----	---	16-22
1979 ^b EPA parameter standards (EPAP)	3	4.3	0.8	
JT9D-7 EPAP ^c values	7	10	5	

^aOptimistic projected value based upon reference 9.^bEPA parameter. (pounds-mass/1000 pounds-force hours/cycle).

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TABLE III. - CATALYTIC COMBUSTOR PERFORMANCE GOALS

Parameter	Engine mode	Program goal
Combustion efficiency	1. Sea-level takeoff	99.9%
	2. Idle	99.5%
	3. All other	99.0%
Pressure loss	All	5%
Altitude relight	Windmilling	Engine relight envelope
Durability Combustor degradation Safety	Satisfactory for all engine conditions	
Development Potential versus overall risk	High with minimum constraints for future implementation	

TABLE IV. - CATALYST MAXIMUM USE

TEMPERATURE PROJECTIONS^a

Availability period	Projection basis	Use temperature limit
Current	Demonstrated, 1000 hr test	1587 K (2400° F) with excursions to 1644 K (2500° F)
Near term (2-3 yr)	Modest catalyst development effort required.	1644 K (2500° F) with excursions to 1700 K (2600° F)
Far term (5-10 yr)	Major catalyst development effort required.	1811 K (2800° F)

^aReference 17.

TABLE V. - GRADED-CELL BED FOR PRESSURE LOSS STUDY

Element no.	1	2	3
Percent bed length	70	15	15
Porosity, percent	75	79	79
Hydraulic diameter, cms	0.635	0.476	0.110
Cell shape	Hexagonal	Hexagonal	Hexagonal

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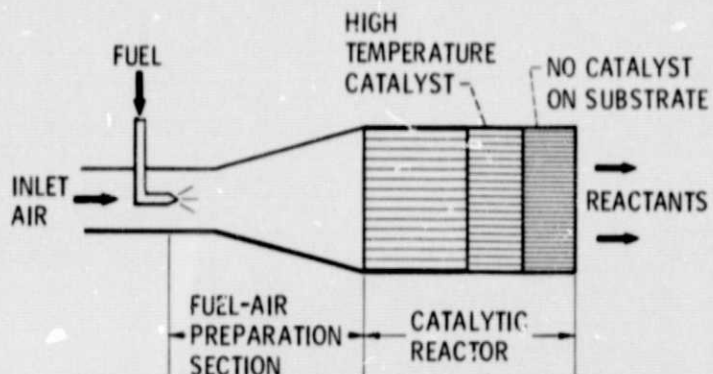


Figure 1. - Schematic of a catalytic combustor.

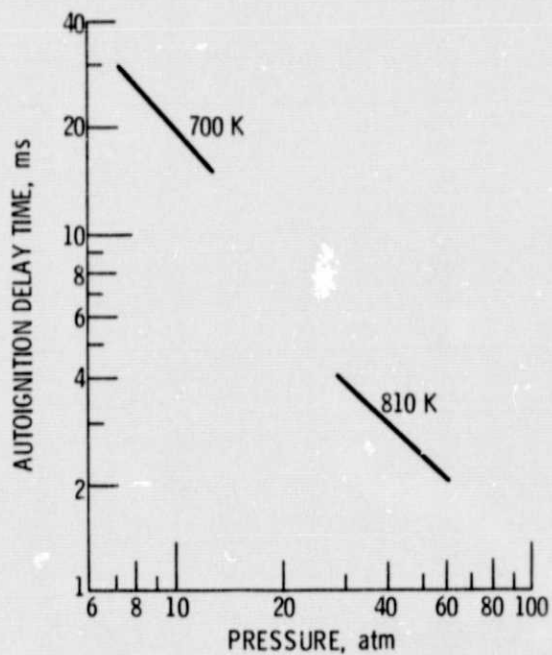


Figure 2. - Jet-A autoignition delay time dependence on pressure and air temperature (ref. 18).

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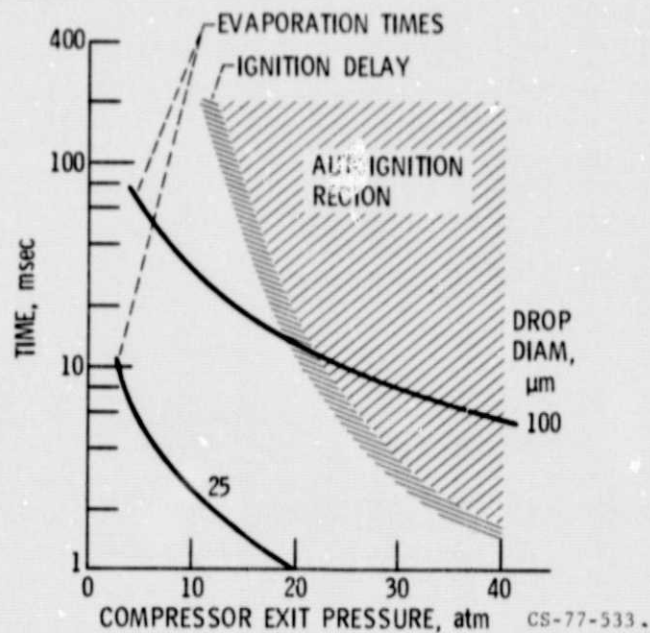


Figure 3. - Jet-A autoignition delay and droplet evaporation times.

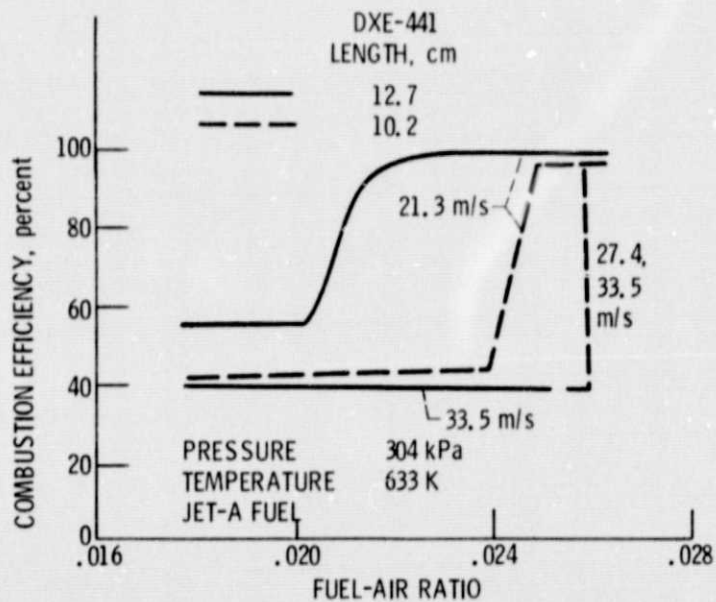


Figure 4. - Catalyst combustion efficiency variation with respect to fuel-air ratio, catalyst length, and catalyst inlet velocity.

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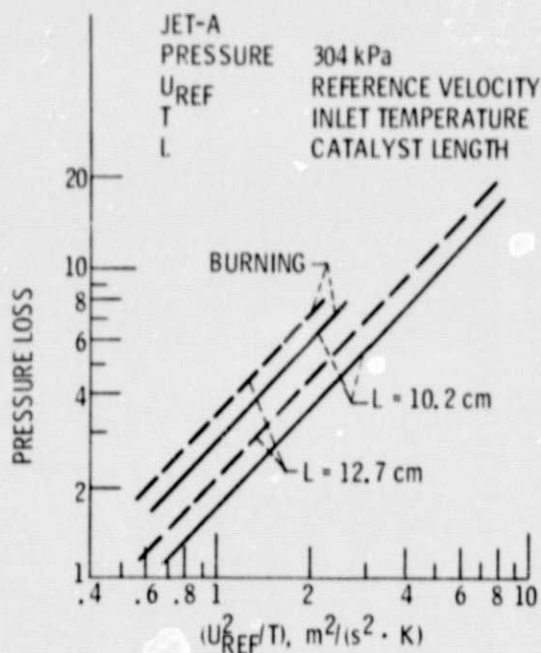


Figure 5. - Isothermal and combustion pressure loss of the DXE-441 catalyst.

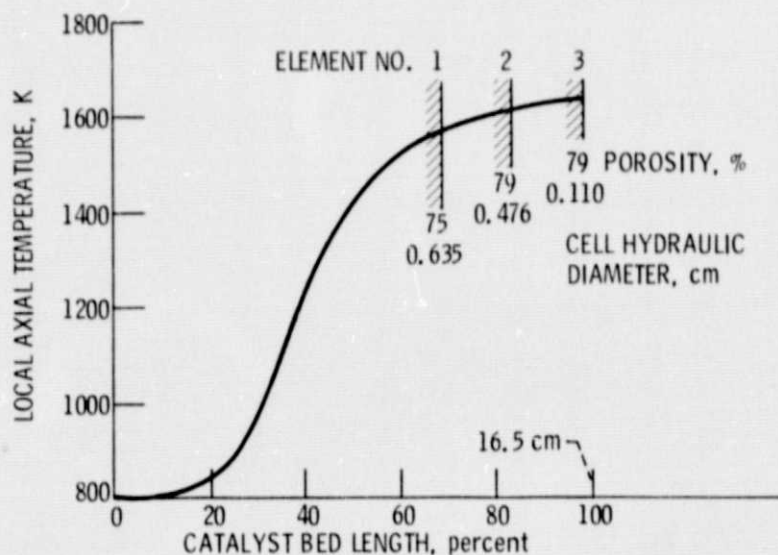
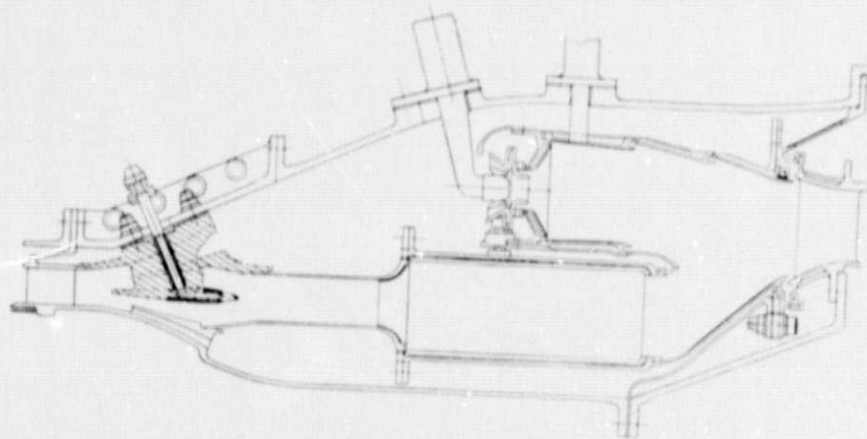
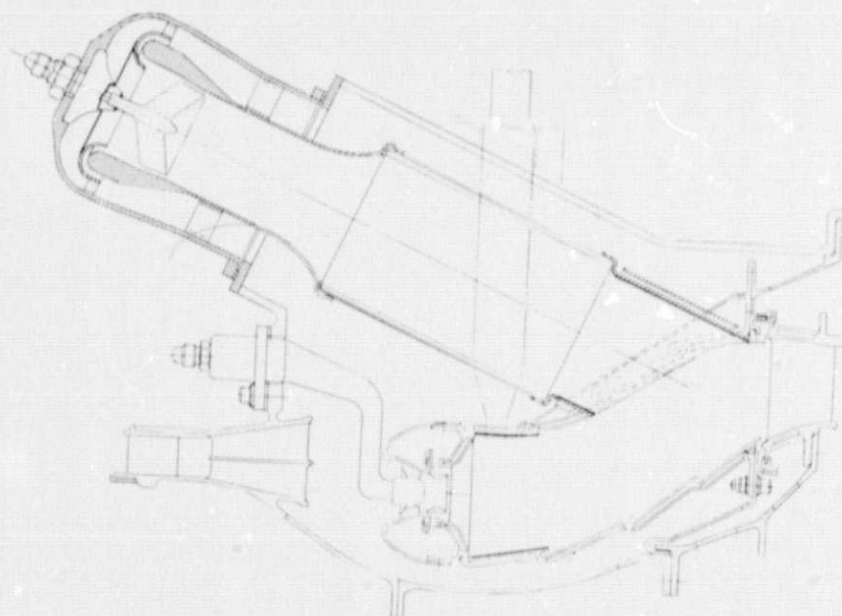


Figure 6. - Estimated axial gas-temperature distribution for the graded-cell catalyst.



(a) BASIC PARALLEL STAGED.



(b) CANNULAR REVERSE-FLOW PARALLEL STAGED.

Figure 7. - Two promising catalytic-combustor concepts of General Electric.

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