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Lean, Premixed, Prevaporized

Combustor Conceptual Design Study

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The objective of this seven month study program is to identify and evaluate promising LPP combustor concepts utilizing variable geometry and/or other flow control techniques. The general approach taken to accomplish this objective is outlined on Figure 1 and consists of combustor design, design analysis and design ranking. The schedule being followed to achieve this program is shown in Figure 2.

Although the ultimate goal of this program is the significant reduction of cruise oxides of nitrogen, both the EPA emission standards and combustor performance levels outlined in Figure 3 are retained as goals as well. The combustor conceptual components are being designed for the cycle and performance characteristics for the Energy Efficient Engine (E^3), currently being developed under a contract with NASA. Representative operating conditions for this engine at the design points of the LTO cycle and for cruise are presented in Figure 4.

The basic design philosophy as listed in Figure 5 underlying all concepts in this program is that of lean, premixed, prevaporized (LPP) combustion utilizing axial-flow full annular designs constrained to the current E^3 configuration. The conclusion to be drawn from the numerous emission reduction programs so far completed, ours as well as others, is that substantial fuel prevaporization, fuel-air premixing, and controlled combustion over the entire engine operating envelope is the only way to reduce all critical emission levels while satisfying engine performance and operational requirements. Achieving the NOx emission goals will require equivalence ratios between 0.5 and 0.6 at reduced residence times while at low power a significantly high equivalence ratio must be maintained to ensure high combustion efficiency and low emissions of CO and THC. This stoichiometry must be controlled while maintaining acceptable combustor pressure drop, adequate cooling and structural integrity.

A variety of techniques were investigated to carry out the design goals of this program. Figure 6 outlines the more important approaches and considerations utilized in establishing the conceptual designs. Since the techniques for reducing low power emissions conflict with methods for reducing high power emissions, the apparent solutions are either a multi-stage combustor wherein each stage is employed and optimized for a particular flight condition or a variable geometry combustor to accommodate optimization of the stoichiometry by means of airflow modulation. The latter approach is more attractive since it can theoretically alleviate the off-design fall-off in performance and associated increase in emissions that has been experienced with previous attempts at employing premixed combustors. The utilization of variable geometry, though desirable from a combustor performance viewpoint, introduces significant complexity and difficulty with respect to combustor design. Reducing the equivalence ratio from 1.0 to 0.50 will require diverting approximately 50% of the combustor airflow. Because of the large change in area involved, the burner designs have to incorporate simultaneous control of front end and dilution zone areas in order to maintain a nearly constant burner section pressure loss. Fuel staging or the incorporation of a pilot stage is also being considered in conjunction with air modulation to optimize the performance of the combustor for starting, ground idle and altitude relight.

Serious consideration must be given to fuel-air preparation to avoid problems with mixedness and incomplete vaporization. Fuel atomization should be as fine as practicable, and the fuel-air residence time must be less than the autoignition delay time.

In designing the premixing passages for the LPP system, precautions have to be taken to avoid potential flow problems, such as wakes behind variable geometry devices and fuel injectors, which could increase the residence time of fuel-air mixture in the premixing passage. Incomplete mixing/vaporization, hence, higher NOx emissions must be weighed against providing adequate margin to avoid autoigition and flashback.

The effect of utilizing large quantities of air in the front end of the combustor on cooling/dilution air requirements is shown in Figure 7a. The implication of this figure, evaluated in conjunction with Figure 7b which shows the effect of increasing combustor pressure on conventional (film-cooled) liner cooling requirements, clearly shows the need for advanced, more effective liner configurations. An additional design consideration is the cooling requirements of the flameholders. The additional cooling requirements of the lean premixed combustor may be alleviated by the reduction of flame radiation.

The four preliminary combustor concepts shown schematically in Figures 8 through 11 are currently being designed and analyzed. As shown, the concepts selected allow evaluation of three variable geometry techniques used in various combinations with advanced burner designs. The techniques include both primary and dilution zone area control as well as an aerodynamic method for varying combustor inlet velocity profile. Mechanical devices will be used to modulating combustor areas while diffuser wall bleed is being considered for the aerodynamic control.

Most of the design problems anticipated with variable geometry LPP systems, shown on Figure 12, have already been mentioned. A most important concern not yet discussed is the control, operation and durability of the variable geometry mechanism itself. The complex air staging techniques will require sophisticated control systems and sensors in order to keep the combustor stoichiometry at desired levels for various flight conditions. The influence of this control system on the overall operation of the engine will have to be evaluated.

Although variable geometry introduces significant complexity and difficulty with respect to combustor design for emissions reduction, it represents a new degree of freedom in turbine engine design. Future engine requirements of higher thrust/weight ratios, higher temperature rise, smaller combustor volume and extended flight envelopes will make it very difficult to achieve both emission and performance requirements. Air staging offers the unique potential of significant improvement in the areas of stability, altitude relight, ground starting and temperature distribution.

OVERALL PROGRAM APPROACH

Objective: Seven month study program to identify and evaluate promising LPP combustor concepts

Task I – Combustor design

- Design four concepts

Task II – Design analysis

- Evaluate for emission, performance, and operational requirements

Task III – Design ranking

- Rate design against requirements
- Rank designs by developmental risk

Task IV – Reporting

FIGURE 1

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PROGRAM SCHEDULE

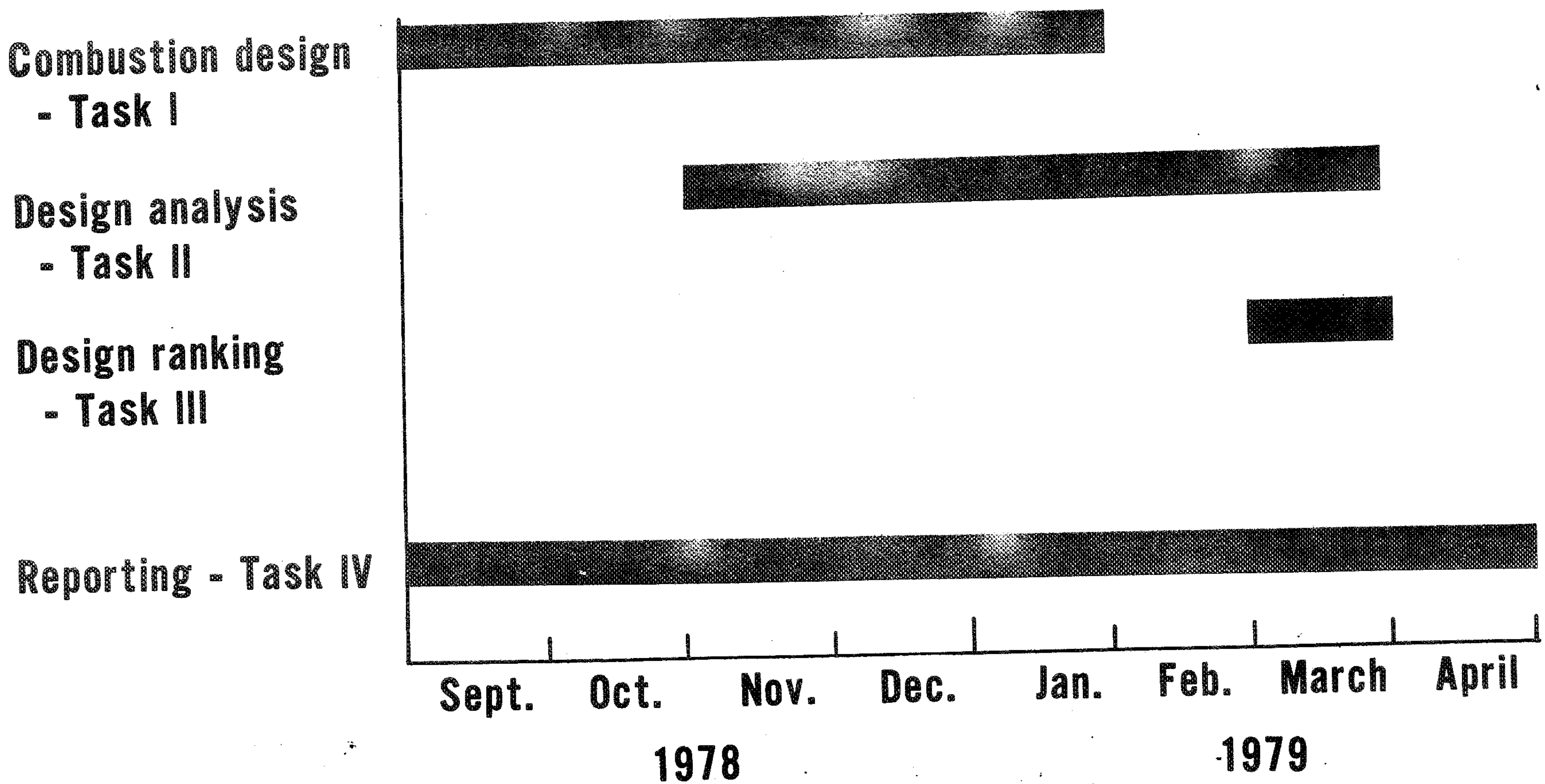

FIGURE 2

PROGRAM GOALS

Emission goals

- NO_x $\in I \leq$ 3g/kg at subsonic cruise
- Meet established standards for LTO cycle

  CO EPAP = 25g/kn

  THC EPAP = 3.3g/kn

  NO_x EPAP = 3 3g/kn

  SAE smoke no.= 20

Performance goals

- Combustion efficiency (η_c)

  η_c 99.9% at SLTO

  η_c 99.5% at idle

  η_c 99.0% at all other operating conditions
- Total pressure loss ($\frac{\Delta P}{P}$) = 5.5% (all conditions except idle)
- Altitude relight $\geq$ 10.7km

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FIGURE 3

PROGRAM DESIGN CONDITIONS

	Ground Idle (a)	Approach	Climb	Sea-level takeoff	Cruise (b)
Combustor inlet temperature (°K)	473	621	777	810	754
Combustor inlet pressure (atm)	4.4	11.7	27.0	31.2	13.8
Air flow rate (kg/sec)	14.0	31.6	62.4	70.2	31.7
Combustor exit temperature (°K)	815	1118	1522	1611	1533
Combustor exit pressure (atm)	4.1	11.0	25.5	29.5	13.1
Fuel flow rate (kg/sec)	0.13	0.43	1.38	1.68	0.74
Overall fuel-air ratio	0.009	0.0137	0.0221	0.0240	0.023

(a) Std day – uninstalled

(b) Alt = 10.7km, Mn=0.8

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FIGURE 4

DESIGN PHILOSOPHY

- Combustor designs shall be axial flow, full annular and constrained to current E^3 configuration and design conditions
- Burn lean ($\phi \cong .5 - .6$) at reduced residence times to achieve NO_X goals
- Burn richer ($\phi \cong 1.0$) at idle and intermediate power levels to achieve THC, CO, and η_c goals
- Control combustion process over the entire engine operations envelope to meet required stability and transient capability
- Establish mechanical integrity

FIGURE 5

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