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Low Emissions Combustor Technology for High-Speed Civil Transport Engines

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HIGH SPEED RESEARCH WORKSHOP

SESSION #7 - EMISSION REDUCTION

NASA HSR OZONE RESEARCH OBJECTIVES

The engine emissions of primary concern are nitrogen oxides (NOx) which, through a series of known catalytic reactions, could adversely impact the earth's protective ozone layer. Although continuing atmospheric studies are needed to fully understand and quantify the levels that would yield no damage, it is clear that technology development focused on reducing NOx emissions is paramount before U.S. industry could commit to a high-speed transport development program. Fortunately, prior emissions reduction programs such as the Department of Energy sponsored research for stationary gas-turbine powerplants indicate that reduction to levels in the range of 3 to 8 grams of NOx per kilogram of fuel burned is possible with advanced combustor design approaches. Further NOx reduction and potential elimination may also be achievable through secondary means such as downstream (post-combustion) injection of chemical reactants.

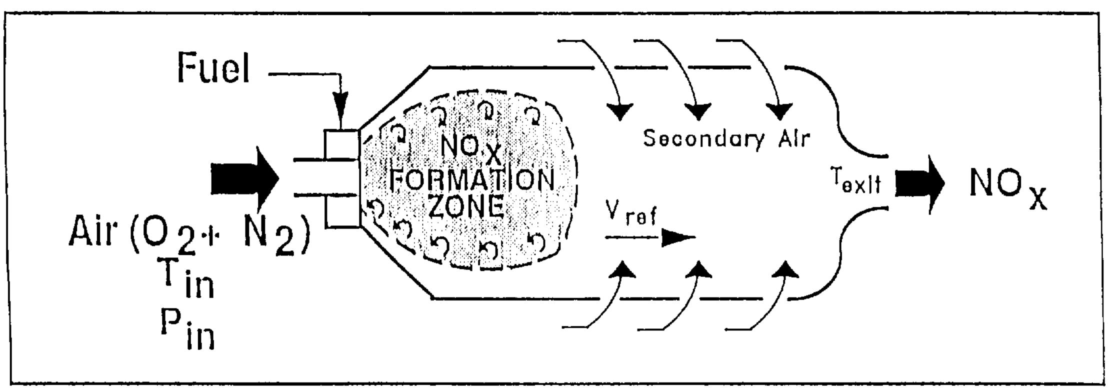
NASA HSR Ozone Research Objectives

- **Determine potential impact of HSCT aircraft fleet on protective ozone layer.**
- **Establish technologies and operational procedures that insure <u>no</u> significant ozone depletion.**

NOx FORMATION

Oxides of nitrogen are formed in combustion systems of engines. In operation, fuel and air are supplied to the combustor and ignited. The subsequent heat produced causes the nitrogen and oxygen in the air to combine to form nitric oxide (NO), lesser amounts of nitrogen dioxide (NO2) and trace amounts of other nitrogen/oxygen compounds. All of these are commonly referred to as oxides of nitrogen or NOx. Two NOx formation mechanisms have been identified; Prompt NOx and Thermal NOx. Prompt NOx results when the combustion process initiates. Fuel hydrocarbon fragments react with air nearly instantaneously to form small amounts of NOx. Due to the speed of the reactions, these processes are essentially uncontrollable. Thermal NOx formation occurs more slowly and is the major production source of this emittant. Formation of thermal NOx is very dependant on temperature levels in the combustor and the length of time that high temperatures persist. Controlling thermal NOx through temperature/residence time management is the major thrust of the emissions program.

NO_x Formation



Prompt NO_x

- **Fast reactions**
- **Hydrocarbon fragments**
- **0–1 gm/kg fuel (E.I.)**
- **Uncontrollable**

Thermal NO_x

- **Slow reactions**

  $N + O_2 \longleftrightarrow NO + O$

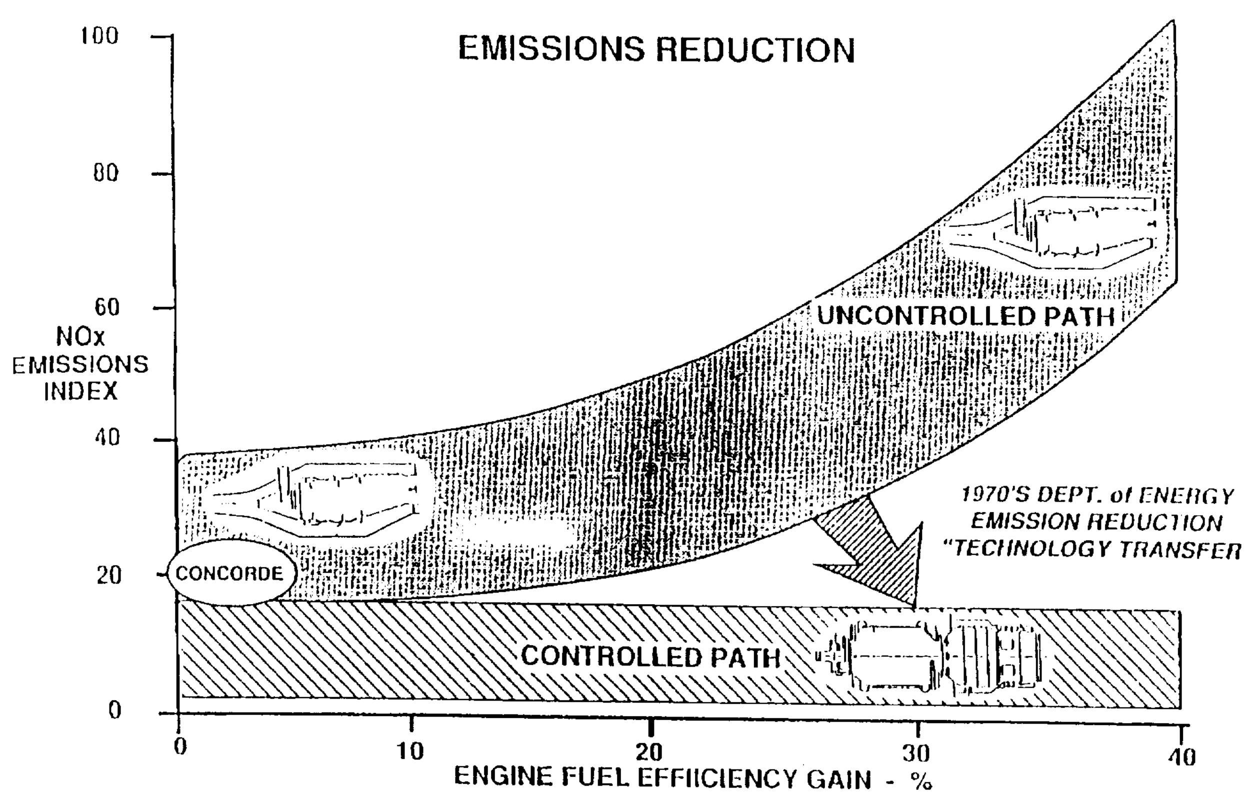
  $N_2 + 3O \longleftrightarrow 2NO + O$
- **Controllable**

Correlation: $NO_x \propto \frac{e^{T_{in}/k} P_{in}^{1/2} T_{exit}}{V_{ref}}$

EMISSIONS REDUCTION

Shown is a plot of NOx emissions against engine fuel efficiency gain. To increase engine efficiency, operation at higher temperatures and pressures is required. These higher temperature and pressure conditions also increase NOx formation. As an example, the Concorde produces a NOx emission index value of 16-20. If energy efficient cycles are employed, NOx values could increase to the large levels indicated by the top band. The objective of this program is to employ very advanced NOx reduction methods to reduce NOx levels to theoretically low levels shown in the bottom band. The technology base for these reductions lie in 1970's emission research and in department of energy research conducted in the late 1970's and early 1980's.

High Speed Research Program



HSCT SUPERSONIC CRUISE COMBUSTION OPERATING CONDITIONS

These conditions are representative of those anticipated to be required for future commercial supersonic aircraft. Future presentations in this session use these conditions as a baseline for data comparison. The operating conditions are much more severe, thus making NOx control more difficult than those projected for prior 1970's supersonic aircraft; in fact, they represent a severity increase of from three to six.

HSCT Supersonic Cruise Combustion Operating Conditions

T_{in}, °F ....1000 - 1350

P_{in}, atm ....12 - 14

T_{exit}, °F...................3000 - 3400

Fuel ....JET-A TSJF
(Thermally stabilized jet fuel)

NOx CORRELATIONS

The severity of combustor operating conditions and their impact on NOx formation can be determined by correlating parameters such as those shown below. Three correlating parameters are listed. Although different in form, they all produce similar results. The (3) subscript refers to combustor inlet conditions; the (4) subscript refers to combustor exit conditions, (Vref) is a measure of velocity in the combustor; (HO) is the relative humidity.

NOx CORRELATIONS

GE;

$$NOx_{EI} = 23.8 \left(\frac{P_3}{432.7 ; psia} \right)^{0.4} e^{\frac{T_3 - 1027.6 ; F}{349.9 ; F} + \frac{6.29 - Ho}{53.2}}$$

$$= 0.0986 \left(P_3 ; atm \right)^{0.4} e^{\frac{T_3 ; K}{194.4 ; K} - \frac{Ho}{53.2}}$$

P&W;

$$NOx_{EI} \sim \frac{P_3^{.5}\, T_4}{V_{ref}} e^{\frac{T_3 ; K}{288 ; K} - \frac{Ho}{53.2}}$$

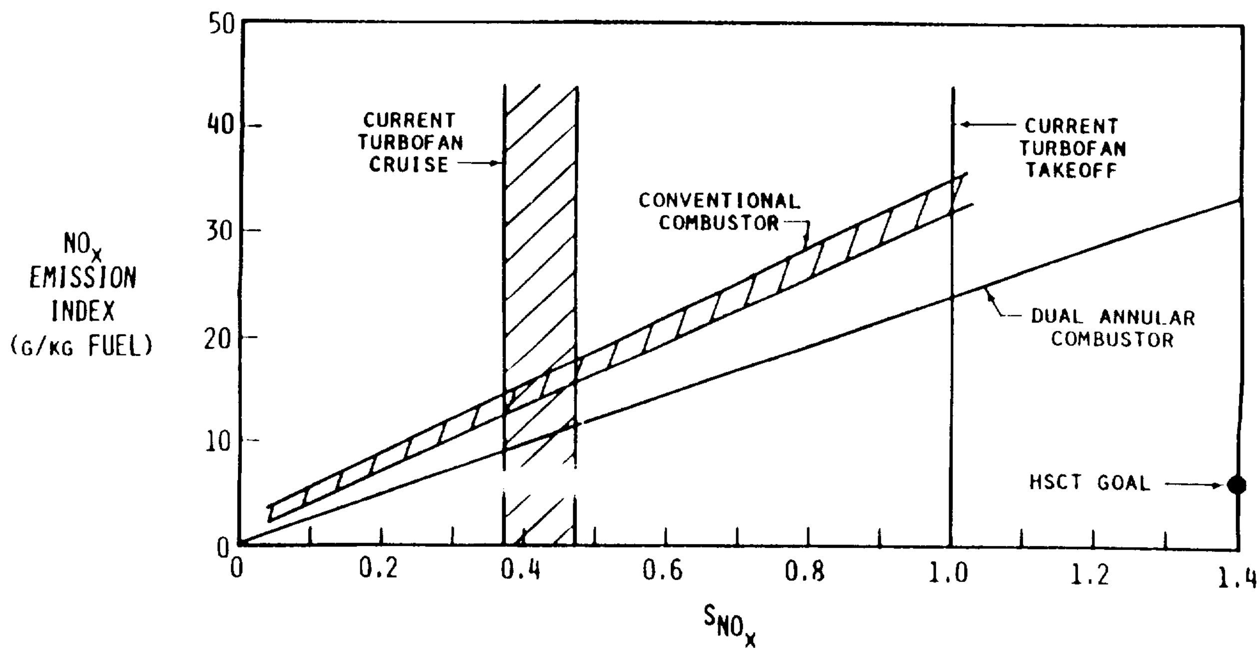
NASA;

$$NOx_{EI} \sim \frac{P_3^{.5}\, T_4}{V_{ref}} e^{\frac{T_3 ; K}{288 ; K}}$$

TYPICAL NOx CHARACTERISTICS OF A CURRENT TECHNOLOGY AND LOW NOX COMBUSTORS

This chart illustrates application of one of the NOx correlating parameters, the GE parameter. The plot is NOx E.I. vs. severity of combustor operating conditions. The top, cross-hatched band indicates NOx characteristics of current, conventional combustors now in use for aeronautical missions. The lower line indicates NOx levels achievable employing the NOx reduction technology evolved in the 1970's for aircraft combustors. As can be seen, considerable additional NOx reduction is required to achieve program goals.

Typical NO_X Characteristics of a Current Technology and Low NO_X Combustors



$$S_{NO_X} = \left(\frac{P_3}{432.7}\right)^{0.4} e^{\left(\frac{T_3 - 1027.6}{349.9} + \frac{6.29 - H_0}{53.2}\right)}$$

HSCT EMISSION REDUCTION STRATEGIES

This chart lists available NOx reduction strategies. Nearly all have merit and should be pursued. However, only low emission combustors offer the potential for NOx reductions approaching the 90 percent level and, thus represents the major thrust of the program. Second stage clean-up consists of the introduction of compounds into the combustor exhaust stream to react with the NOx to produce benign elemental nitrogen. This approach, while being employed for terrestrial emission control, will be very difficult- possibly impossible- to employ on flight systems. However, its applicability, because of its very low NOx potential, is currently being studied.

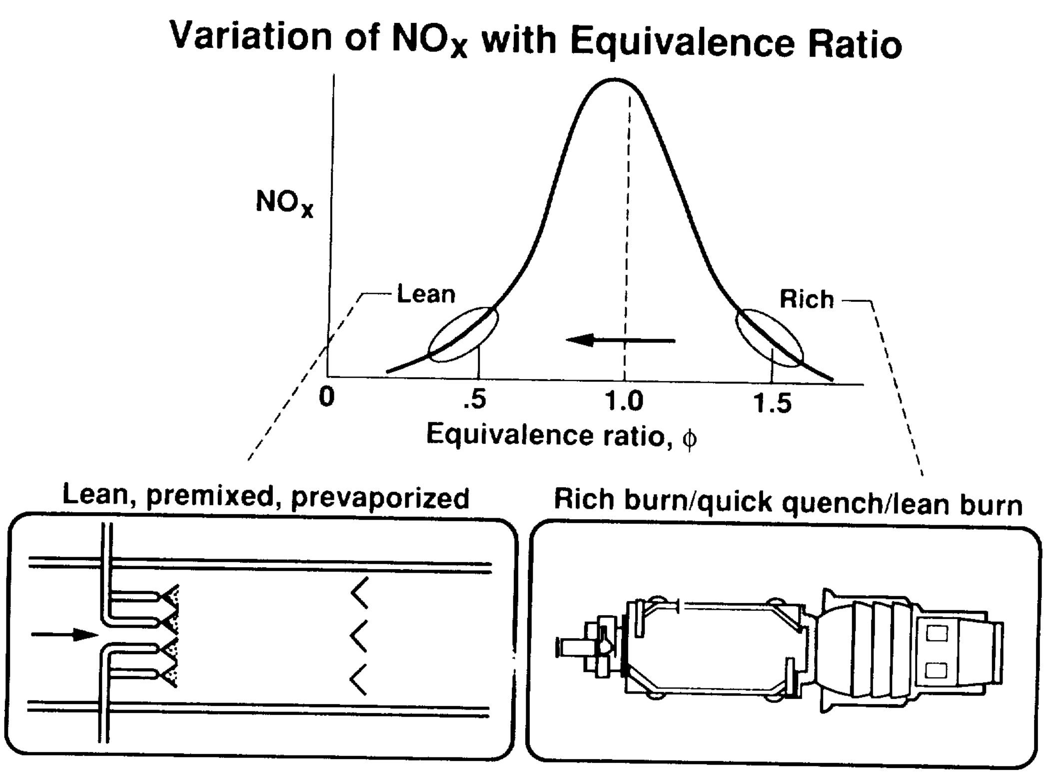
HSCT EMISSION REDUCTION STRATEGIES

STRATEGY	EXAMPLE APPROACH	NO_X ASSESSMENT STATUS
Advanced Airframe	High L/D & Low $W_{Structure}$	~ 20 to 30% Reduction
High Efficiency Engine	Supersonic Throughflow Fan Advanced Core	~ 20 to 40% Reduction
Modified Engine Cycle	Combustor Pre-Cooling Reduced Cycle T & P	Excessive HX Size Excessive Efficiency Loss
Low Emission Combustors	Lean Pre-Mixed / Pre-Vaporization Rich Burn / Quick Quench / Lean Burn	~ 80 to 90% Reduction (EI ~ 5) *
Second Stage Cleanup	NO_X Destruction Additives	EI → 0 Potential * - Very High Risk

* Extrapolation of Terrestrial Data Base

Variation of NOx with Equivalence Ratio

The figure below illustrates the principle that NOx production is a maximum near a stoichiometric equivalence ratio (1.0) where there is a "perfect" mixture of fuel and air such that all of the fuel is burned with all of the air to produce combustion products. If combustion occurs in a lean mixture (excess combustion air), or in a rich mixture (excess fuel), lower flame temperatures occur and lower NOx emissions are produced. This is the basis for the two major concepts shown schematically in the figure. The Lean-Premixed-Prevaporized (LPP) concept continually burns a lean mixture to produce low NOx. The Rich Burn Quick Quench/Lean Burn (RQL) concept burns rich in the first stage of combustion, quickly quenches the mixture to minimize the time spent near stoichiometric, then burns lean in the final stage of combustion. These two concepts are the main contenders for the future low NOx combustor for the HSCT.



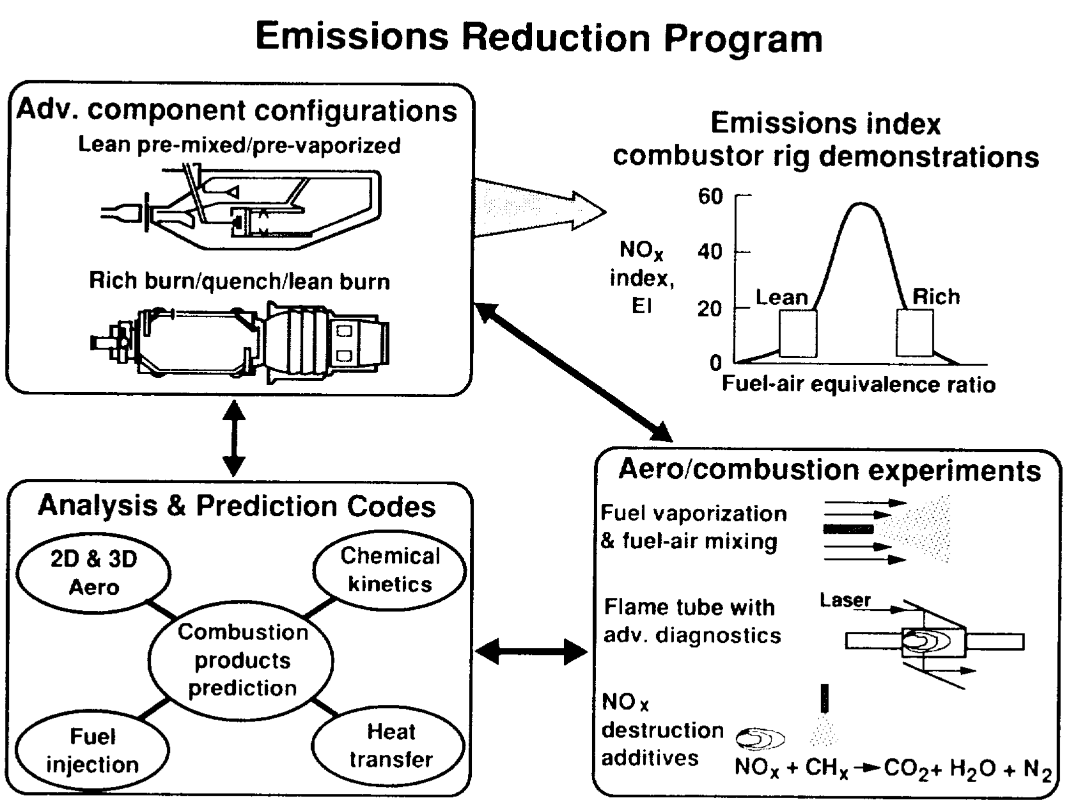
EMISSION REDUCTION PROGRAM

The approach to emissions reduction technology development couples both analytical and experimental capabilities which first build a strong fundamentals foundation, and then integrates and applies that knowledge base to engine-level combustor hardware for verification.

Analysis codes are used to assess proposed concepts for screening and to also identify areas of concerns requiring lab experiments for resolution. Enhancements to the codes will occur throughout the program.

Lab experiments are the primary source of the knowledge base. Results define key design factors, foster formulations of alternate concepts, and demonstrate achievable NOx reduction levels.

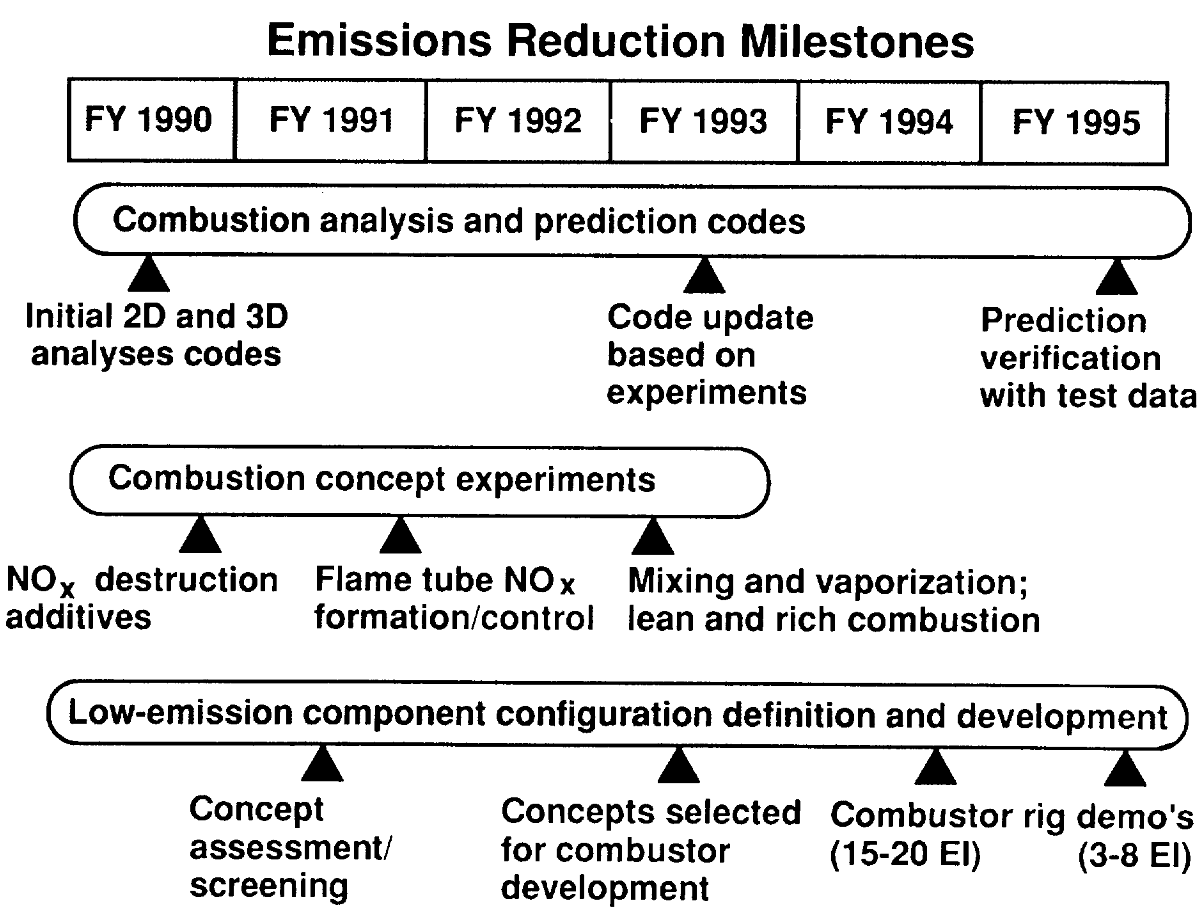
Development of low-emission combustors will be accomplished by; evolving key sub-components such as the fuel injectors, and mixing devices; integrating them in selected combustor designs; and, development tests at simulated operating conditions.



EMISSION REDUCTION MILESTONES

This chart illustrates the program elements and key milestones. Program success depends on achievement of all milestones. However, the most critical are the following:

- o FY91: Demonstrate ultra-low NOx levels in flame tube experiments conducted at simulated supersonic cruise conditions.
- o FY92: Select the prime combustion approach for combustor development.
- o FY95: Demonstrate ultra-low NOx levels in combustor test rigs.



SUMMARY

This chart briefly describes current program status.

Summary

- Flame tube experiments have been initiated to demonstrate ultra low NO_x emission levels for LPP; to be evaluated in 1991 RQL combustion approaches.
- Stable of existing computer codes being evaluated/upgraded/ validated to analyze low emissions combustor concepts
- Efforts with engine companies are in process to evaluate combustor concepts leading to selection of prime approach at end of FY 1992.