DOE/NASA/1062-79/3
NASA TM-79313
(NASA-TM-79313) LOW NO(X) HEAVY FUEL COMBUSTOR PROGRAM (NASA) 15 p HC A02/MF A01 CSCL 10B
N80-13624
Unclas
G3/44 46300

LOW NO_X HEAVY FUEL COMBUSTOR PROGRAM

Eric Lister
Department of Energy

and

Richard W. Niedzwiecki and Lester Nichols
National Aeronautics and Space Administration
Lewis Research Center

Work performed for
U.S. DEPARTMENT OF ENERGY
Energy Technology
Fossil Fuel Utilization Division

Prepared for
Twenty-fifth Annual International
American Society of Mechanical Engineers
New Orleans, Louisiana, March 9-13, 1980

DOE/NASA/1062-79/3
NASA TM-79313

LOW NO_x HEAVY FUEL COMBUSTOR PROGRAM

Eric Lister
Department of Energy
Germantown, Maryland

and

Richard W. Niedzwiecki and Lester Nichols
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Prepared for
U.S. DEPARTMENT OF ENERGY
Energy Technology
Fossil Fuel Utilization Division
Washington, D.C. 20545
Under Interagency Agreement EC-77-A-31-1062

Twenty-fifth Annual International
Gas Turbine Conference sponsored by the
American Society of Mechanical Engineers
New Orleans, Louisiana, March 9-13, 1980

ABSTRACT

The "Low NOx Heavy Fuel Combustor Program" is a part of the DOE/LeRC "Advanced Conversion Technology Project" (ACT). The program is a multiple contract effort with funding provided by the Department of Energy, and technical program management provided by NASA LeRC. Main program objectives are to generate and demonstrate the technology required to develop durable gas turbine combustors for utility and industrial applications, which are capable of sustained, environmentally acceptable operation with minimally processed petroleum residual fuels. The program will focus on "dry" reductions of oxides of nitrogen (NOx), improved combustor durability and satisfactory combustion of minimally processed petroleum residual fuels. Other technology advancements sought include: fuel flexibility for operation with petroleum distillates, blends of petroleum distillates and residual fuels, and synfuels (fuel oils derived from coal or shale); acceptable exhaust emissions of carbon monoxide, unburned hydrocarbons, sulfur oxides and smoke; and retrofit capability to existing engines.

INTRODUCTION

This paper describes the Low NOx Heavy Fuel Combustor Concept Program including its objectives, program plan, schedule, the basis for its emphasis on heavy oil and synfuels, pollution and performance goals, program approaches to pollution reduction, and status to date.

The gas turbine is viewed by DOE and NASA as being particularly attractive for industrial and utility power generation because of its low production/installation costs and short installation time (which could be very important by 1985 if coal and nuclear steam plants continue to have the siting and emission cleanup difficulties they now appear to be encountering). In addition, the gas turbine has emerged from various studies in industrial cogeneration as a multi-industry winner for high return on investment (in the range of 20 to 50 percent in the Cogeneration Technology Alternatives Study). Several factors exist, however, which impact upon the ability of the gas turbine to be highly utilized in the industrial and utility market. These are:

1. Limited near and mid-term fuel supplies, as well as competition from other users of natural gas, light and mid-distillates could make it attractive for utility and industrial gas turbine manufacturers and users to fire residual oils in their gas turbine equipment. Present combustor technology must be advanced in order to use these fuels in an acceptable fashion. Since future fuel supply options are limited, but uninterrupted operation is mandatory, stationary gas turbines of the future must be capable of firing a wide range of fuels. In addition to petroleum residual fuels, future fuel supply options will include synthetic fuel oils from coal and shale (synfuels). Successful utilization of synfuels represents a still more difficult challenge due to their anticipated increase in impurity content, lower hydrogen-carbon ratio and high levels of fuel bound nitrogen.

2. Exhaust emissions from future gas turbines must meet federal emission standards. Also, under limited circumstances, stationary gas turbines may be required to produce ultra-low emissions using presently available clean fuels due to stringent local environmental regulations. Oxides of nitrogen emission standards are difficult to meet with current

light distillate fuel oils, and will become more difficult with residual oils and synfuels. Water or steam injection has been successful in some installations to reduce thermal NOx formation. However, this approach is clearly not a universally acceptable method since it involves considerable additional installation and operational costs, and does not reduce NOx from fuel bound nitrogen. Smoke will also increase with heavy fuel firing as a result of lower fuel hydrogen content.

It appears that substantial reduction of pollutants can be attained. The concepts for pollution reduction now exist. However, although the mechanisms of pollution production as well as techniques for reducing pollutants are generally known, application of these techniques to specific combustor engine designs has not yet demonstrated the anticipated pollutant reductions without compromising other combustor parameters. Thus additional technology is needed to apply these concepts. The Low NOx Heavy Fuel Combustor Concept Program was initiated to provide a timely evolution of clean combustors.

3. Cogeneration is currently a small and shrinking market in the United States. This is due principally to non-technical reasons involving institutional, legal, as well as regulatory problems. However, in the future it is anticipated that increasing petroleum fuel prices and limited supplies will generate pressure on users to implement cogeneration systems. Availability of gas turbine technology capable of using alternate fuels will add to the attractiveness of cogeneration.

The program aim is to develop the required pollution reduction and fuel flexibility technology, apply the technology to combustors for industrial and utility applications, solve interface and performance problems which low pollutant combustor designs create for engine installation, and demonstrate the pollution reductions in steady state and transient testing of development engines.

PROGRAM DESCRIPTION

General

The Low NOx Heavy Fuel Combustor Concept Program is a multi-year contract effort funded by the Department of Energy and administered by the NASA Lewis Research Center. The program's primary objectives are the following:

1. To generate and demonstrate the technology required to develop industrial and utility gas turbine engine combustors capable of sustained, environmentally acceptable operation with minimally processed heavy oil fuels.
2. To accelerate implementation of fuel-flexible combustors for industry/utility gas turbine systems, emphasizing near-term heavy oil utilization.
3. To permit substitution of heavy oils for light distillate fuels and natural gas in the near term.
4. To permit transition to synthetic liquid fuels when they become available.
5. To investigate and develop the technology required to achieve ultra-low emissions (one-half the EPA NOx standard) with current clean distillate fuels.
6. To demonstrate the derived technology in full scale engines.

The program is primarily applicable to near-term industrial and utility engines suitable for cogeneration applications. Additional applicability is desired for future, higher pressure ratio engines.

PROGRAM PLAN

It is anticipated that the program will be conducted in three phases. An overall program diagram is contained in Figure 1. Program phases are discussed below:

Phase I - Combustion Technology Generation

This phase, which is currently in the process of being implemented, consists of combustion studies, fuel studies, development of combustion designs, tests, and retests of multiple combustion concepts to determine the best concepts for achieving program objectives. The specific objective of Phase I is to generate the emission reduction and fuels technology required for future program phases. This phase, with the exception of the brief descriptions of Phases II and III presented directly below, is the subject matter of this paper. As with all program phases, Phase I is a contract effort. Multiple contracts have been initiated with Solar Division of International Harvester, Detroit Diesel Allison Division of General Motors, General Electric Corporation, Westinghouse Corporation and United Technologies Corporation.

Phase II - Combustor Screening and Optimization

This phase will consist of incorporating the Phase I combustion results into engine-combustor hardware, component testing of promising combustor concepts, iterative redesign and retest of multiple combustor design approaches to determine the best combustor approaches for achieving program goals, and development of combustor liner designs suitable for heavy fuel utilization. The most promising combustor designs will then be tested further to develop the required overall performance, durability and engine adaptability required for engine utilization. Eligible contractors for this phase will not be restricted to those contractors completing the Phase I effort. One or more contractors are visualized.

Phase III - Engine Verification

This phase will consist of evaluating the best combustor(s) of Phase II as part of a complete engine. The intent is to demonstrate in short duration engine testing the emission reductions achieved, fuel flexibility and performance at steady-state and transient conditions. Contractors for this phase will be restricted to those contractors successfully completing the Phase II effort. One or more contractors are visualized.

Since the program emphasizes utilization of minimally processed heavy petroleum fuels, and since burning of petroleum distillates, distillate residual blends and synfuels will be assessed but not optimized, the possibility exists for additional program efforts regarding these latter fuels, which are not a part of the current program. Also, if feasible, additional program efforts involving installation of the derived combustors in field engines for extended evaluation may be undertaken. These potential efforts are contained in dashed lines in Figure 1.

PROGRAM SCHEDULE

The planned program schedule is shown in Figure 2. Phase I efforts were initiated in September, 1978 with issuance of NASA RFP 3-870802.

Contract signings began in March, 1979, with completion of this phase scheduled to occur within 16 months of contract signing. An approximate six-month delay is anticipated between the completion of Phase I and the initiation of Phase II, due to procurement procedures. Phase II will be approximately 30 months in duration. It is anticipated that Phase III will be initiated immediately upon completion of Phase II, with finalization occuring during Phase II. Phase III will be approximately 16 months in duration.

FUELS CONSIDERATIONS

Fuels Availability

Limited near, mid-term and far-term petroleum fuel supplies, as well as competition from other users of scarce fuels, could make it attractive for utility and industrial gas turbine manufacturers and users to utilize more abundant fuels to fire their gas turbine equipment. However, the subject of which feed stock will form the base for gas turbines used in stationary applications in the future is especially problematic at this time. Convincing arguments can be made that the country must come to grips with using synfuels made from abundant national supplies (Table 1) of coal, oil shale and tarsands in order to achieve the national goal of reducing dependence on foreign energy supplies.

There remain questions as to whether and when synthetic fuels will be available for industrial/utility gas turbines. At present, synthetic liquid fuels are quite difficult to acquire even for test and development purposes. In addition, synthetic feed stocks could be converted by additional processing and hydrotreating into fuels for the transportation sector. Thus, although ground based gas turbines could utilize synfuels, other users could provide sufficient competition for them that industrial users would have a difficult time purchasing them economically. It is expected, however, that success in this program would provide a major input to establishing major marketing and processing information needed by 1985 in order to establish coal/shale refining sites in the late 1980's.

The oil burned by utilities today in steam plants is predominantly a residual grade. If, as anticipated, steam plants convert to coal utilization in the future, quantities of residual fuels could be available for other applications such as ground based gas turbines. Present gas turbine combustor technology must be advanced in order to use these fuels in an acceptable fashion. This in turn could free-up the distillate fuels these gas turbines now use for other uses such as the commercial, residential and transportation sectors.

In this program, residual, distillate, synfuels and fuel blends will be investigated. Table 2 shows the similarity of a heavy petroleum residual and some examples of coal-derived liquids. The petroleum residual and synfuels tend toward higher levels of fuel bound nitrogen and lower hydrogen content both of which have a direct effect on the emissions of a gas turbine. Thus, much of the technology required to make environmentally acceptable use of petroleum residuals can be applied to synfuels. The ability of heat engines to use synfuels with acceptable emissions and acceptable durability will help determine the economic feasibility of synfuels. To be economically competitive, synthetic liquids must be minimally processed, i.e., hydrogenation of coal-derived crudes must be kept to an absolute minimum.

Phase I Test Fuels

Three test fuels have been specified for Phase I. These fuels are described in Table 3. Fuel A is a petroleum distillate simulating Diesel #2 properties. The objective of testing with this fuel will be to achieve ultra-low NOx which is defined as one half the applicable EPA standard. Ultra low NOx combustors are required in areas where local regulation, more stringent than the EPA standard are in effect.

Fuel B is a petroleum residual fuel and is the major basis for combustion design in this program. Correspondingly, test efforts will emphasize utilization of this fuel. Fuel C is a synfuel obtained from the solvent refined coal (SRC) process. It is anticipated that if available in sufficient quantity, additional synfuels will be included in the test program.

In addition to testing with the fuels defined above, additional fuel tests will also be conducted in Phase I. Test fuel B will be doped with pyridine to investigate combustion approaches for reducing fuel bound nitrogen conversion. Levels up to 0.5% by weight of fuel bound nitrogen will be investigated with fuel B.

In addition, blends of fuel A with fuel B, and blends of fuel A with fuel C will also be investigated. The objectives of these tests are: to determine the tradeoffs concerning fuel quality and its effects on combustor emissions and performance.

Several of the difficulties anticipated to be encountered are shown in Table 4. Increased alkali metal content of heavy fuels are anticipated to create corrosion and deposition problems on combustor liners and turbine blades. Increases in boiling range increase tendencies of gum formation and carbon deposition on fuel nozzles and combustor liners. Reduced hydrogen content causes increased radiation during combustion, thus producing increased heat loading to combustor liners and adversely affecting combustor durability. Fuel bound nitrogen conversion into NOx makes achievement of the NOx standard, which is at best marginally achievable at present, more difficult to attain. All of these effects impose additional requirements on the combustor designs. The purpose of this program is to address and satisfactorily overcome these difficulties.

Emission Goals

Program emission goals are based on EPA Proposed Regulation, F.R. 40 CFR Part 60 and are subject to all of the constraints and corrections contained in this citation. The emission goals are contained in Table 5. Engine operating conditions for which the goals apply are discussed in a subsequent section. These operating conditions incorporate all engine power levels for load following engine-combustors.

The sulfur dioxide goal represents a limitation on fuel sulfur, since all of the fuel sulfur is transmitted through the combustor. It is included here for consistency with the referenced citation. Subsequent program phases will address the question of fuel sulfur to local regulation. An S.A.E. number of 20 is consistent with advanced state-of-the-art combustor design practices.

Achievement of the oxides of nitrogen (NOx) standard represents the most difficult program goal for achievement. Water or steam injection to reduce oxides of nitrogen by reducing flame temperatures will not be relied upon as a control device in this program. "Dry" reductions of oxide of nitrogen through combustor design will be sought. At present, the technology required to control NOx through the combustor design is not available, even with clean distillate fuels. The current NOx emissions will have to be reduced by a factor of two to three to meet goals shown in Table 3. There are also indications that achievement of the NOx standard value will be more difficult to achieve with heavy fuels. This is shown in Figure 3.

Fuel bound nitrogen levels in the fuel also make achievement of the NOx standard more difficult. Current EPA regulations permit correction for fuel bound nitrogen up to 0.25%. Fuel bound nitrogen levels in excess of 0.25% must be compensated for by reducing the conversion of fuel nitrogen into NOx. Typical fuel bound nitrogen conversion data, for a current production industrial engine are shown in Figure 4. It is anticipated that additional emission goals will be added to future program phases. For example, a particulate goal is anticipated for program Phases II and III.

Performance Goals

Key combustor performance goals are listed in Table 6. With the exception of combustion efficiency these goals represent values achievable with current gas turbine combustors. Thus these goals represent limits up to which performance parameters can be increased in pursuit of the pollution goals.

The combustion efficiency goal effectively imposes maximum allowable levels of unburned hydrocarbon (HC) and carbon monoxide (CO), since levels of these emissions are directly relatable to combustion inefficiency. Conversely, program measurements of combustion efficiency are specified to be recorded through emission level determinations. Current combustors operate very efficiently at high engine power points (50% of engine rated power level and above). However at lower engine power levels, especially at spinning idle conditions, combustion inefficiencies occur with most current engines.

Test Conditions

Combustor test conditions over which the emission and performance goals apply are contained in Table 7. Implicit in the selection of these test conditions is a requirement for load following capability. Load following capabilities are deemed to be necessary for this program because cogeneration applications for the derived technology are visualized. Most industrial and utility gas turbine engine combustors operate efficiently at a nominal base load condition and somewhat less efficiently at off-design or lower power conditions. The requirement that engine combustors operate efficiently over a load range is a significant requirement. To achieve this type of operation, combustor performance must be optimized for a variety of combustor inlet conditions, including those of low temperature, pressure and fuel/air ratio.

Combustor Considerations and Design

Advanced combustor designs will be emphasized in the Phase I program. A non-inclusive list of pollution reduction techniques which will be investigated in the program are contained in Table 8. Included in the table is the pollutant of concern and the corresponding pollution reduction concept.

Control of thermal NOx involves reduction of flame temperatures below 3000°F and short residence times of combustion gases at high temperatures. Simultaneous control of thermal NOx and smoke additionally requires uniform distribution of fuel and air, and avoidance of excessively high fuel rich zones. Control of the conversion of fuel bound nitrogen into NOx involves burning under fuel rich conditions or, correspondingly, oxygen lean conditions.

The technology developed in Phase I should be applicable to all types of gas turbine combustors. An illustration of these types is contained in Figure 5. Most current ground based gas turbine combustors are of the can or can-annular type.

Two of the types of combustor designs which will be investigated are contained in Figure 6. Single stage combustors represent current technology. Multizone combustors represent advanced technology which is currently being evolved for both ground based and aircraft gas turbine combustors. Multizone designs, while considerably more complex than current designs, provide additional degrees of flexibility in staging fuel and combustion to optimize performance for a variety of test fuels, emission and performance constraints.

CONCLUDING REMARKS

It is anticipated that Phase I of this program will provide the technology base for future program phases. Specifically it is anticipated that Phase I will provide the following:

1. Definition of the most promising combustor design approaches for utilizing heavy fuels derived from petroleum and other sources.
2. Definition of tradeoffs involving fuel quality and combustion and emission performance.
3. Identification of realistic fuels for future program phases.
4. Identification of engine applications for the derived technology. This will include preparation of conceptual engine-combustor designs.
5. Identification of development efforts required to utilize minimally processed heavy fuels in sub-component combustor areas such as fuel systems, liners, etc.

TABLE 1. - U.S. REMAINING FUEL

RESOURCES (APPROXIMATE)

	10^{15} Btu	H/C Ratio
Petroleum	700	2.00
Synthetic fuels*		
Tar sands	100	1.75
Oil shale	20 000	1.90
Coal	90 000	0.75

Liquid fuel consumption U.S. $40x10^{15}$ Btu/year

*Fossil fuels derived from other than petroleum.

TABLE 2. - LIQUID FUELS FOR DIRECTLY FIRED ENGINES

Key characteristics	Todays standard	Near-term heavy petroleum	Mid-term minimally processed coal derived					
			Exxon* donor solvent	Licht* d.stil-late	H-coal*		SRC	
	=2 Distil-late	Residuals			Heavy distil-late	Resid-uals	I-Light distil-late	II-Heavy* distil-late
Fuel bound nitrogen, wt %	0.06	0.05 to 0.5	0.7	0.42	1.01	1.3	1.5	1.3
Hydrogen/carbon (atomic ratio)	1.8	1.3	1.09	1.38	1.01	1	.8	1.01
Ash, wt %)	----------	0.05	0.03	Nil	Nil	0.2	0.2	Nil
Sulfur, @t %	0.5	0.5 to 2.7	0.6	0.18	0.22	0.48	0.8	0.3
Pour point, ^{o}F	-10 to 20	40 to 70	20	-100	86	115	500	110

*Product is assumed to contain no ash and alkalis since vacuum distillation is performed.

TABLE 3. - FUEL PROPERTIES

	Fuel A petroleum distillate	Fuel B petroleum residual	Fuel C SRC-II blend
Specific gravity	0.839	Report	0.999
Hydrogen, wt %	12.8 ± 0.2	11.3 ± 0.3	8.6 ± 0.2
Sulfur, wt %, max	0.2	0.8	0.2
Ash, wt %, max	Report	0.04	0.02
Pour point, °F, max	-5	65	-55
Flash point, °F	140	---------------	160
Viscosity, cst, 100° F	1.0	>45 (furol sel)	4.5
Nitrogen, wt %	<0.02	<0.3	0.9 to 1.1
Distillation temperature			
IBP °F	310	---------------	~340
FBP °F	620	---------------	~700

TABLE 4. - FUEL CONSIDERATIONS AND IMPACTS

Parameter	Fuel types			Effect
	Current #2	Heavy oils	High F.B. nitrogen	
Alkali metal content	Low	High	Higher	Corrosion & deposition
Typical boiling range, °F	380-650	600-1000	600-1000	Gumming & carbon formation
Hydrogen content wt %	12.2-13.2	10-12.5	9-12.5	Luminosity + smoke
Thermal NO_x	High for all in relation to stds.			
F.B. Nitrogen	0-0.2	0-0.5	0.5-1.2	NO_x conversion

TABLE 5. - EMISSION GOALS

Pollutant	Maximum level	Operating condition
Oxides of nitrogen[1]	75 ppm at 15% O^2	All
Sulfur dioxide[1,2]	150 ppm at 15% O^2	All
Smoke[3]	S.A.E. number = 20	All

Notes:

1 EPA Proposed Regulation, F.R. 40 CFR Part 60.

2 Limit of fuel sulfur content.

3 No EPA Regulation, local rules.

TABLE 6. - PERFORMANCE GOALS

Combustion efficiency*	>	99% at all operating conditions
Total pressure loss	<	6% at base power load
Outlet temperature pattern factor	=	0.25 at base load and peak load power
Combustor exit radial temperature profile	=	Equivalent to production comb. values

*Calculated on a deficit basis from measurements of CO, THC and CO_2.

TABLE 7. - PROPOSED COMBUSTOR TEST CONDITIONS

Cold start
Spinning idle
30% Rated power
50% Rated power
70% Rated power
80% Rated power - nominal base load condition
100% Rated power - peak load condition
Parametric variation

TABLE 8. - POLLUTION REDUCTION TECHNIQUES

Pollutant	Reduction concepts
Thermal NO_x reduction	Diluent injection into burning zone; Quick quench; Catalytic combustion
Thermal NO_x and smoke reduction	Premixed/prevaporized burning; Ultra lean burning; Advanced fuel injection; Multiple fuel utilization
Organic NO_x conversion reduction	Rich burning with controlled quench

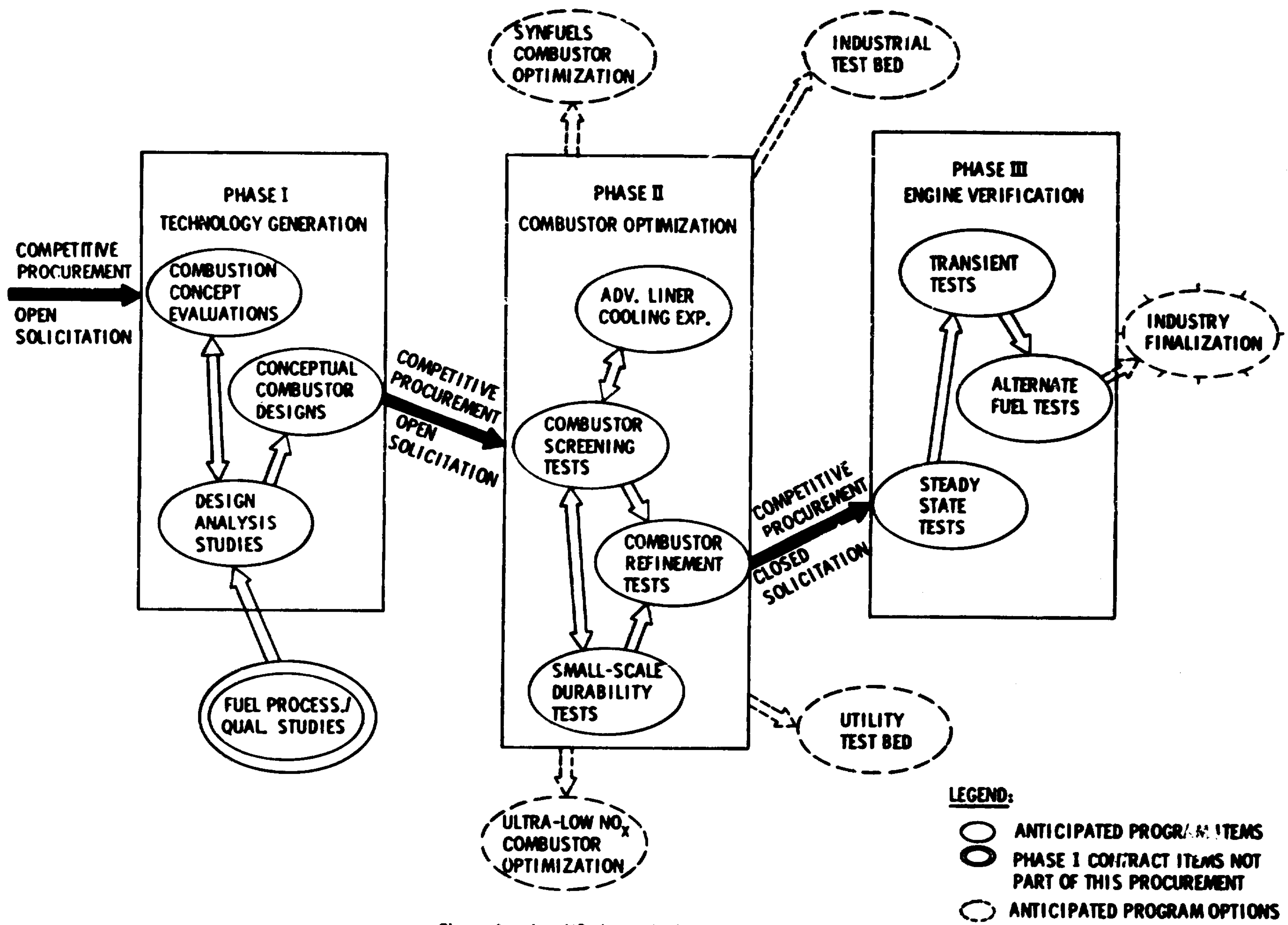


Figure 1. - Low NO_x heavy fuel combustor program.

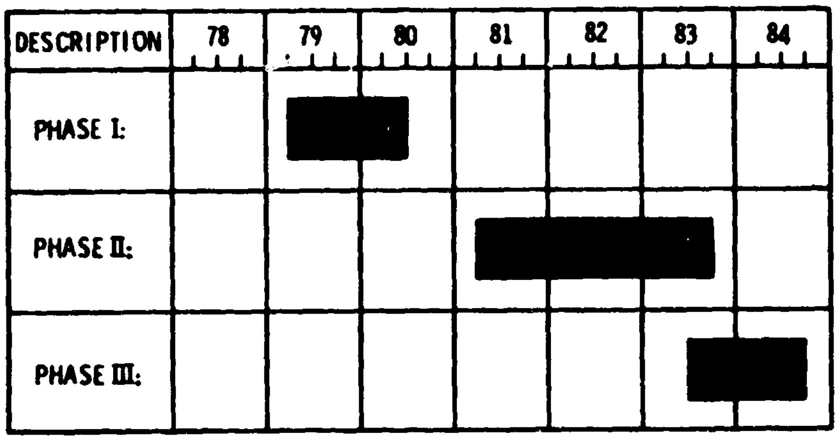


Figure 2. - Proposed program schedule.

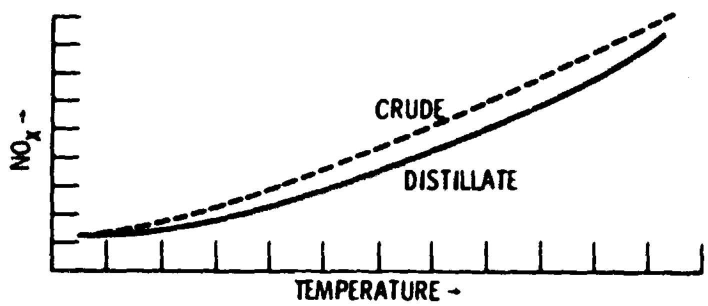


Figure 3. - Thermal NO_x considerations (typical combustor).

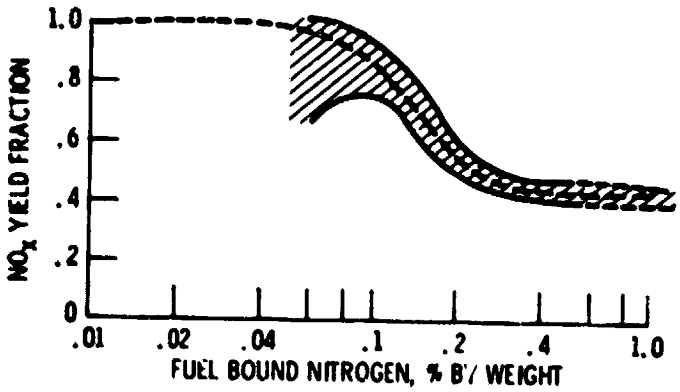
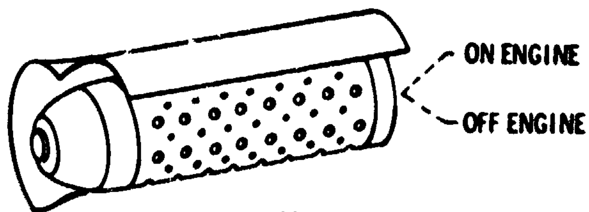
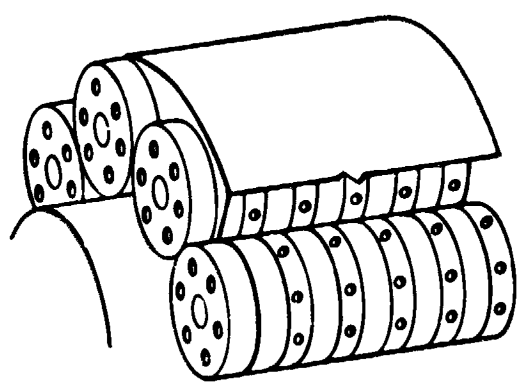


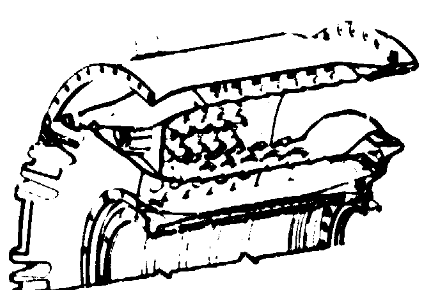
Figure 4. - Fuel bound NO_x considerations.



CAN



CAN-ANNULAR



ANNULAR

Figure 5. - Potential combustor types.

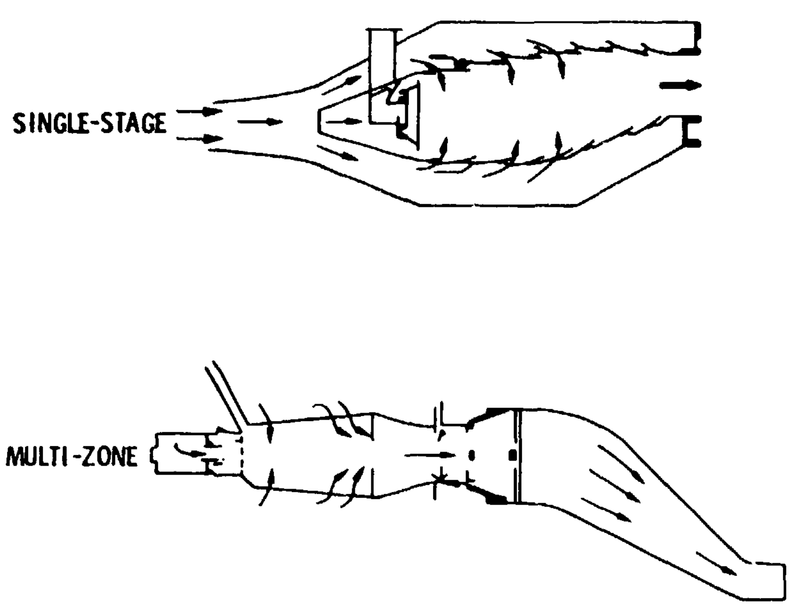


Figure 6. - Combustor designs.