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STUDY OF RESEARCH AND DEVELOPMENT REQUIREMENTS OF SMALL GAS-TURBINE COMBUSTORS

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Arthur D. Little, Inc.



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16. Abstract <p>The objective of the study was to identify the R&D efforts which must be conducted in the 1980-1990 time frame in order to meet the critical needs of combustors for small aircraft gas-turbine engines (1490 kw or less). A survey of the major small-engine manufacturers and governmental users was conducted. An invitational forum was then convened at NASA-Lewis to reach a consensus regarding small-combustor requirements.</p> <p>The results presented are based on an evaluation of the information obtained in the course of the study. The current status of small-combustor technology is reviewed. The principal problems lie in liner cooling, fuel injection, part-power performance, and ignition. Projections of future engine requirements and their effect on the combustor are discussed. The major changes anticipated are significant increases in operating pressure and temperature levels and greater capability of using heavier alternative fuels. All aspects of combustor design will be affected, but the principal impact will be on liner durability. An R&D plan which addresses the critical combustor needs is described. The plan consists of 15 recommended programs for achieving necessary advances in the areas of liner thermal design, primary zone performance, fuel injection, dilution, analytical modeling, and alternative-fuel utilization.</p>			
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FOREWORD

An important part of the study consisted of surveying the major manufacturers and governmental users of small turbine engines and organizing an invitational forum of these organizations to reach a consensus regarding combustor needs. The findings contained in this report represent our analysis and interpretation of the individual comments and opinions expressed in the course of the study, as well as information available in the general literature. In resolving sometimes conflicting views as to required emphasis, we have made every attempt to present a balanced perspective of the problem areas. The results, hopefully, provide an objective assessment of the needs and priorities of R&D efforts in the small-combustor field.

The authors wish to deeply thank Carl Norgren of NASA-Lewis for his valuable guidance and advice in planning and conducting the study described here. We also wish to express our heartfelt gratitude to the organizations and individuals interviewed for devoting so much of their time in meeting with us and providing us with needed information. We are particularly grateful to the members of the forum working group listed in Table I who contributed so much to achieving a candid and open discussion of the problem areas. A special final note of thanks and acknowledgement is due to consultants Prof. Arthur H. Lefebvre and E. Roy Norster who actively assisted in our efforts and provided the needed insights into the unique size-related problems of small combustors.

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I. SUMMARY

A study has been performed for NASA-Lewis to identify the research and development efforts which must be conducted in the 1980-1990 time frame in order to meet the critical needs of combustors for small gas-turbine engines. The principal focus was on aircraft propulsion engines of less than 1490 kw (2000 hp) power level.

The study consisted of reviewing the current status of small-combustor technology, projecting the direction of future requirements in the field, and identifying and prioritizing the specific R&D programs which should be conducted in order to satisfy the anticipated requirements. The approach which was used involved an initial survey of the major manufacturers and governmental users of small engines. This was followed by an invitational forum of these organizations, convened for the purpose of reaching a consensus regarding future goals and how to achieve them. The results presented here are based on a critical evaluation of the information and opinions obtained in the course of the investigation.

Present-day small engines operate at cycle pressure ratio and turbine inlet temperature in the ranges of 6/1-17/1 and 1200-1530°K (1800-2300°F), respectively. Light-distillate fuels are used in virtually all applications. Increasing demands for better fuel economy will require significant increases in pressure and temperature levels. The projections for future engines indicate pressure ratios may be in the range of 12/1-25/1 and turbine inlet temperatures in the range of 1480-1700°K (2200-2600°F). In addition, decreasing availability and rising prices of conventional fuels will most likely create a strong incentive to use less-refined alternative fuels in future engines.

There are a variety of size-related problems associated with the design of small combustors. The principal difficulties in current applications lie in achieving acceptable liner cooling, atomization, uniformity of circumferential fuel/air distribution, part-power efficiency, and ignition. The severity of these problems will increase as a result of the projected changes in future engine requirements. The principal impact will be on liner durability. Significant advances in this area will be necessary in order to cope with the increased thermal loading associated with the combustion of heavier fuels at higher pressure and temperature levels.

Research and development efforts are needed in all aspects of combustor design and operation. The key requirements are development of efficient liner cooling techniques and materials, optimization of primary-zone performance, and improvement of the characteristics of small fuel injectors. Advances are also needed in the areas of dilution-zone design, analytical modeling, and alternative-fuel utilization. A comprehensive plan involving 15 separate R&D programs which address the critical combustor needs has been developed. The

recommended programs represent a broad-based and effective approach to achieving the required advances in small-combustor technology.

II. INTRODUCTION

II.1 Background

Historically, the principal utilization of the gas-turbine engine has been in large-scale aircraft applications where its advantages, such as high power-to-weight ratio and reliability, far outweigh its disadvantages, such as relatively poor part-load efficiency and high cost. The inherent advantages over alternative prime movers decrease with power level. General aviation is a large application area falling within the range of power levels over which the gas turbine loses its competitive edge. Recent years have seen a rapid and continuing growth in the general aviation industry. In addition, advances in technology have made the use of turbine engines in lower-power applications considerably more attractive than in the past. As a result, there exists a large potential for a significant expansion of the market for small turbine engines (ref. 1). The opportunity for growth lies not only in the upper end of the general aviation power spectrum, where the gas turbine has traditionally been dominant, but also in the portion of the market currently shared with reciprocating engines. In order to fully realize the potential, however, a number of size-related problem areas need to be addressed and solved.

The small turbine engine is distinguished from its larger counterpart not so much in terms of overall requirements, but rather in the severity of the problems associated with achieving these requirements. Although manifested in a variety of ways, the basic difficulty is one of geometric scale. As power level is reduced, the required dimensions of the various engine components also decrease whereas manufacturing tolerances remain fixed. As a result, compromises must be made which reduce the achievable efficiency and increase the difficulty of attaining acceptable performance, reliability, and durability in a practical configuration. Although most components suffer from scale-down problems, the combustor is particularly susceptible because essentially all aspects of its design and performance are affected. An examination of the unique problems associated with small combustors is an integral part of any overall effort aimed at advancing the technology of small gas-turbine engines.

The vast majority of the gas-turbine research and development sponsored in the past has concentrated on large engines. Relatively little attention has been paid to the lower-power applications which fall under the category of general aviation. In recognition of this fact and because of the growing importance of the general-aviation field, NASA has embarked on a comprehensive effort devoted to addressing the particular needs of small gas-turbine engines (ref. 2). As part of this effort, the NASA-Lewis Research Center is currently engaged in a program specifically dealing with small-combustor technology. Arthur D. Little, Inc., has provided assistance to NASA-Lewis in its planning of this program by conducting a study of the research and development needs of small combustors under Contract No. NAS3-21980.

II.2 Scope of the Study

The principal focus has been on combustors for turboprop or turbo-shaft engines of 1490 kw (2,000 hp) or less. The selected upper limit of 1490 kw was judged to be a conservative estimate of the value below which "small-engine effects" start to become evident. The main emphasis has been on defining the combustor needs for general-aviation engines. In the course of gathering the necessary information, we have also examined briefly the technology of APU and automotive turbine engines. This was done for completeness in order to take advantage of any existing opportunities for useful technology transfer, since these applications share a number of problem areas and potential solution approaches with engines in the low end of the general-aviation power spectrum.

The primary objective of the study was to formulate a comprehensive research and development plan for implementation by NASA-Lewis in the 1980-1990 time frame, which adequately addresses the needs of small gas-turbine combustors. As indicated in Figure 1, the investigative process for achieving this involved several key elements:

- Examining the trends in the various factors which are expected to have the major influence on small-engine requirements.
- Projecting the specifications which will have to be met by future engines.
- Determining the corresponding combustor requirements in terms of the pertinent design, performance and operational characteristics which must be achieved.
- Examining the anticipated requirements in relation to the state-of-the-art methodology and technology in order to identify the specific advances that are needed.
- Defining and prioritizing the research and development efforts which must be carried out to attain the required advances.

The final goal in conducting the study was to evaluate the needs in the small-combustor field and recommend for support by NASA-Lewis in the 1980's the specific programs which are most worthwhile pursuing in the various technology areas of concern.

II.3 Approach

The responsibility for the success of the small gas turbine ultimately rests with the major users and manufacturers of this class of engine. These organizations as a group represent the principal repository of the information necessary to effectively plan the technical efforts required for small combustors. They will also be influential in insuring that the developed plan is successfully implemented. Consequently, the study was structured so as to insure the direct and

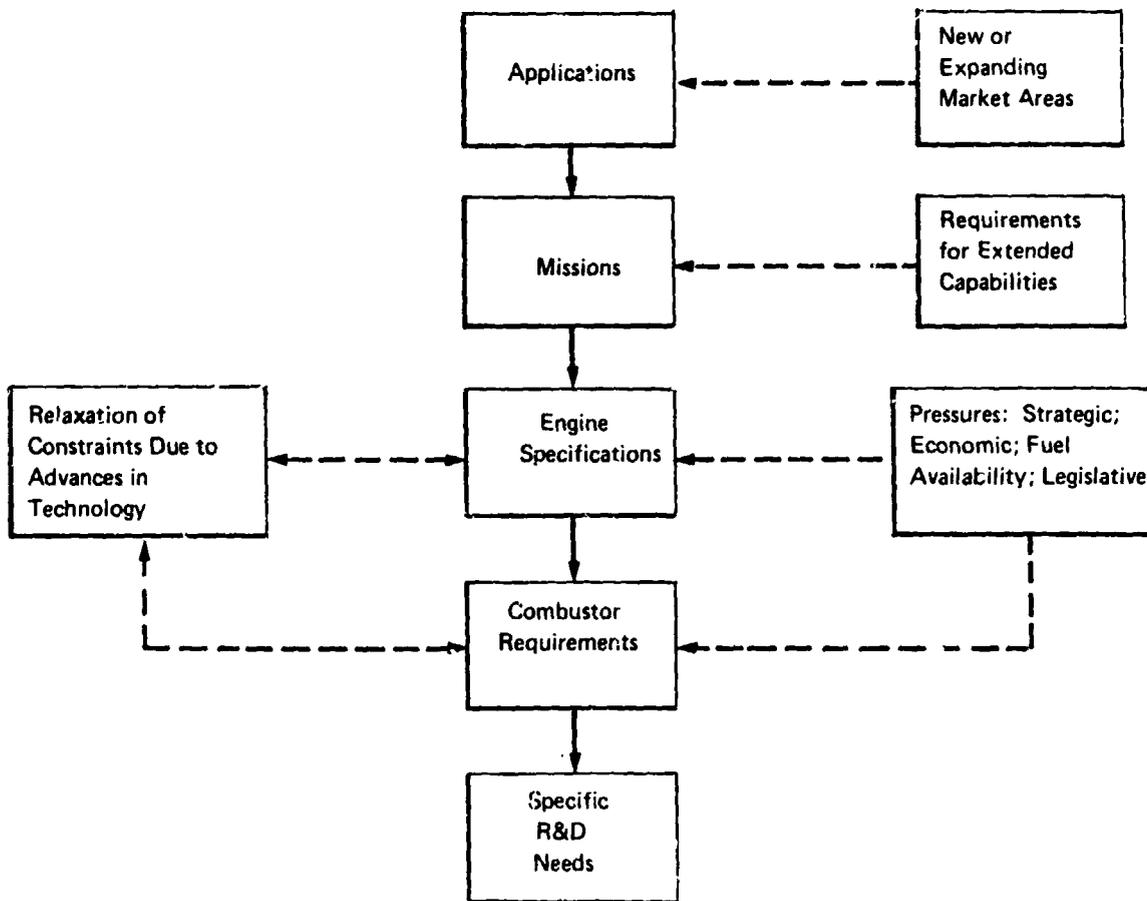


Figure 1. Schematic of interrelationships among major factors influencing R&D requirements.

active participation of these organizations in formulating the requirements for properly addressing the needs of small combustors.

The initial portion of the study consisted of a review of the available information to tentatively identify the specific problem areas and issues which needed to be addressed. This formed the framework for conducting a subsequent comprehensive survey of the major organizations active in the small-engine field. Representatives of Arthur D. Little, Inc., visited each of these organizations and held in-depth discussions with the personnel responsible for combustion activities. The discussions concentrated on obtaining detailed answers to a variety of questions regarding the current status of small-engine technology, the direction of future requirements, and the developments over the next ten years which are perceived as being necessary to satisfy the anticipated requirements.

Following the completion of the survey, our evaluation of the information and opinions obtained was presented in a report which was issued to all participants (ref. 3). These preliminary findings served as the focus for a 2-day invitational forum of the organizations surveyed. This was held at the NASA-Lewis Research Center on November 14-15, 1979, and was attended by the organizations and individuals listed in Table I.

The purpose of the forum was to provide the participating organizations with the opportunity to critically review and comment on the preliminary findings and, through open discussions of the problem areas, to reach a consensus regarding the required technical efforts which should be pursued. The major portion of the forum was structured around a number of individual sessions dealing with the different combustor technology areas of concern. Each session consisted of a presentation by ADL of the recommended R&D programs based on our preliminary survey, followed by a full group discussion aimed at modifying and expanding the list of suggested programs. At the completion of the discussions in each session, the representatives of each participating organization were requested to fill out questionnaires rating the different programs discussed on the basis of several categories including relative priority, estimated level of effort, sequencing, and timing. The rating sheets were collated by ADL representatives and a summary of the results was presented to the group in the concluding session of the forum. This served as the focal point for an open discussion of the complete list of suggested research and development programs. As the final step in the forum process, each of the participants was asked to select the programs which are most worthwhile conducting and to rank them in order of importance.

The information and opinions obtained in the course of the study have been critically reviewed and analyzed in light of the conclusions reached in the forum. The final results, which are documented in the remainder of this report, reflect our interpretation of the consensus of all participants in terms of the required goals in the small-combustor field and the approaches necessary to achieve them.

TABLE I. - PARTICIPANTS IN SMALL-COMBUSTOR FORUM

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III. REVIEW OF CURRENT TECHNOLOGY

III.1 Application Areas

This study concentrates on aircraft propulsion engines of less than 1490 kw (2000 hp) or 6.8 kg/s (15 lb/s) core airflow, including turboprop, turboshaft and turbofan types. Using this general power level limit to distinguish "small" from "large" engines is based on our best judgment and is, admittedly, arbitrary. There is no single feature, component, or application dissimilarity that can be used to differentiate between "small" and "large" engines. For example, if attempting to categorize turbofan engines, the bypass ratio and fan pressure ratio, as well as core performance, determine engine thrust. This precludes the use of any of these parameters alone to define "small" turbofan engines. In selecting the power range of interest for this study of small combustor problems, however, we concluded that engines of less than 1490 kw or 6.8 kg/s core airflow generally possess common characteristics and require design considerations which tend to set them apart from larger engines.

Small aircraft turbine engines are found in the following applications:

- Manned airplanes (turboprop/fan/jet)
--military, commercial transport, general aviation.
- Helicopters.
- Cruise missiles and remotely piloted vehicles.
- Aircraft auxiliary power units (APU's).

For the purposes of this study, we have concentrated on primary propulsion for airplanes and helicopters (turboprops, turboshafts, turbofans). In keeping with NASA's mission and directives, APU's and specialized military applications (missiles, etc.) were not specifically addressed except where these engines establish a benchmark for small turbine development and where research will benefit the industry as a whole. Cooperation and coordination is important, however, because future constraints in development funds will provide strong pressure to design components with multi-use capability.

Turbine power has been accepted in nearly all fixed and rotary wing aircraft with engines over 370 kw (500 hp) because of advantages in flight speed, payload, aircraft gross weight, passenger safety/comfort, and allowable cruise altitude when compared with piston engines. Time Between Overhaul (TBO) intervals are also significantly longer and, although Specific Fuel Consumption (SFC) and first cost are higher than for piston engines, life cycle costs are characteristically lower. No other current power plant than the small gas turbine can provide as acceptable a balance among these different design requirements.

Today, small turbine engines are used almost universally in helicopters and commercial carriers (commuter airlines) and are rapidly filling a gap in twin engine business aircraft in the Mach Number (M) = .4 to .8 cruise range. They are also in control of the target-drone/RPV market, and are rapidly moving into the long range missile area (ref. 4). The only remaining market untouched by small gas turbines is the single and small twin engine, fixed-wing general aviation aircraft. Participants in the NASA-sponsored GATE study (refs. 5, 6, 7, 8) predict sizeable penetration in this area with 450-kw-and-under gas turbines in the years ahead if appropriate research and development programs are pursued.

III.2 Mission Requirements

The current aircraft small turbine engine operational envelope (Mach number vs cruise altitude) is quite broad. Turbines are capable today of operating at altitudes above 22.9 km (75,000 ft) and speeds above Mach 2. Near-term improvements promise to extend this capability to near 30.5 km (100,000 ft) and Mach 3. For state-of-the-art turboprops, this envelope is reduced to below approximately Mach 0.5 and 12.2 km (40,000 ft). For turboshaft engines (helicopters), the envelope is further limited to Mach 0.2 and 6.1 km (20,000 ft).

III.3 Basic Engine Characteristics

The small engine class addressed in this study can be further broken down into three sub-categories which can tend to utilize somewhat different design philosophies, components, materials, etc.:

- 1) less than 300 kw (400 hp)
- 2) 300-745 kw (400-1000 hp)
- 3) 745-1490 kw (1000-2000 hp)

A schematic of a "typical" engine found in sub-categories (2) and (3) is shown in Figure 2. A low-pressure axial compressor and high-pressure centrifugal compressor are driven by an uncooled axial turbine (engines over 745 kw (1000 hp) are beginning to use some cooling as turbine inlet temperature exceeds 1310°K (1900°F)). A reverse-flow annular combustor is representative of the industry although straight annular combustors are found in some models. A separate power turbine provides shaft output power for propulsion in all helicopter applications because of rotor coupling considerations, as well as in most turboprops. Engines of less than 300 kw (400 hp) are similar to that shown in Figure 2 although centrifugal compressors, radial turbines, and can combustors may be used.

Figures 3 and 4 show the range of engine pressure ratio and turbine inlet temperature vs engine power level for current engines. For aircraft propulsion engines, pressure ratio ranges from 6/1 to 17/1 with 8/1 to 9/1 being most common. Turbine inlet temperature ranges from approximately 1200°K (1700°F) to 1530°K (2300°F). Average specific fuel consumption is approximately 1.0×10^{-4} kg/kw-s (.6 lb/hp-hr).

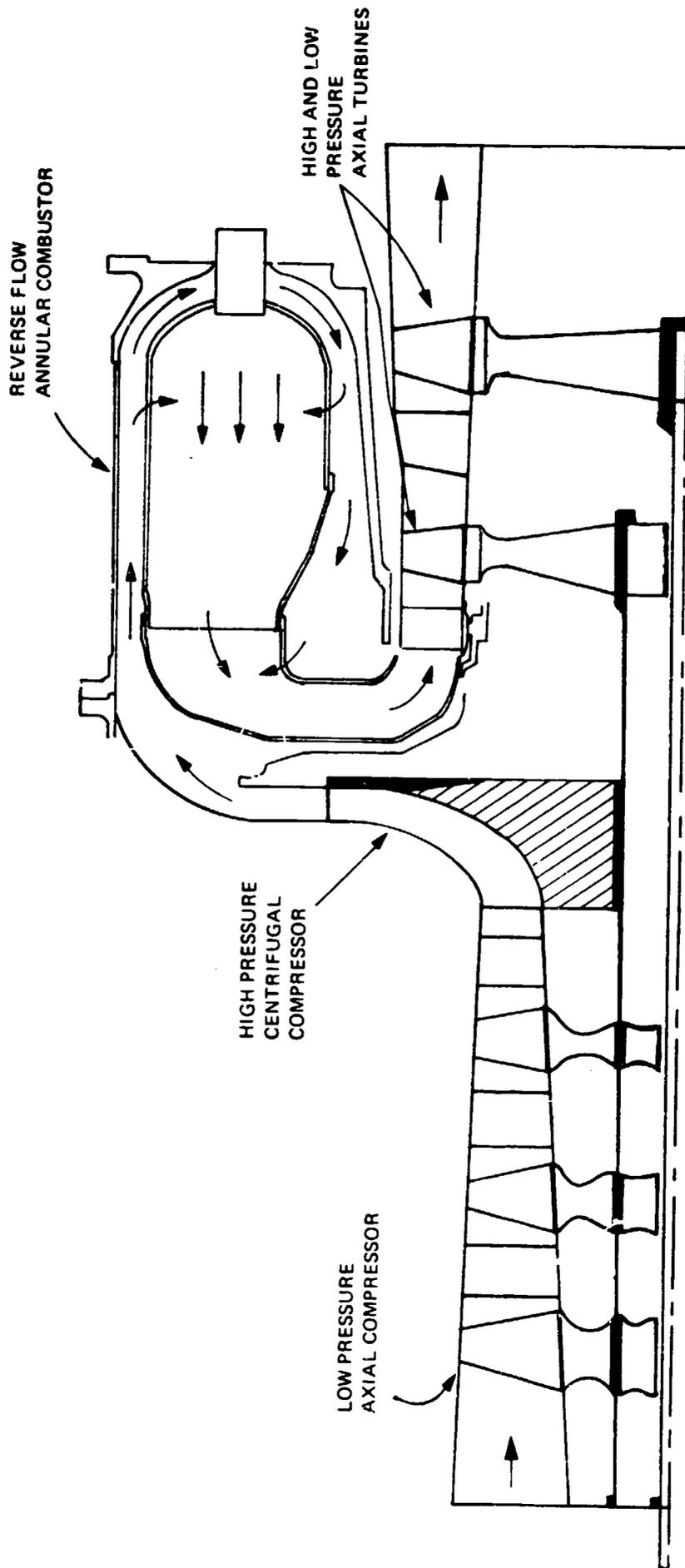


Figure 2. Representative configuration for a small gas-turbine engine.

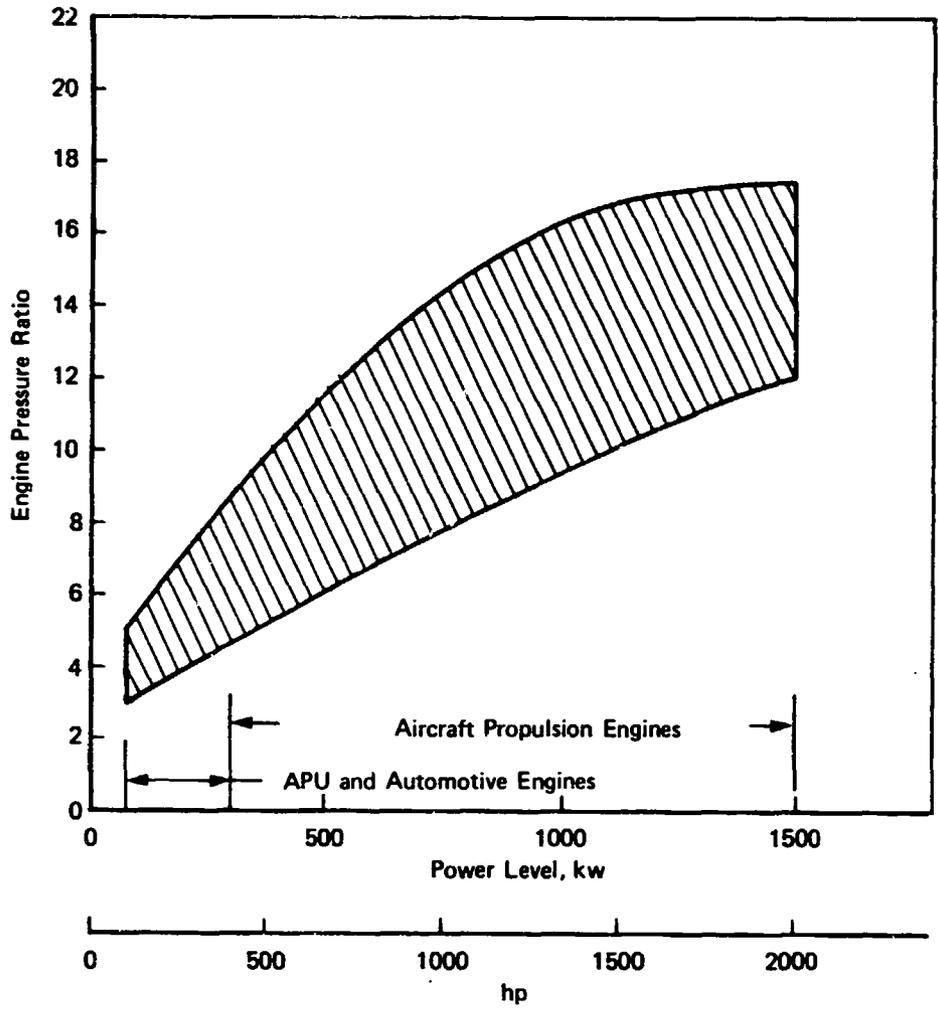


Figure 3. Range of pressure ratio in current engines.

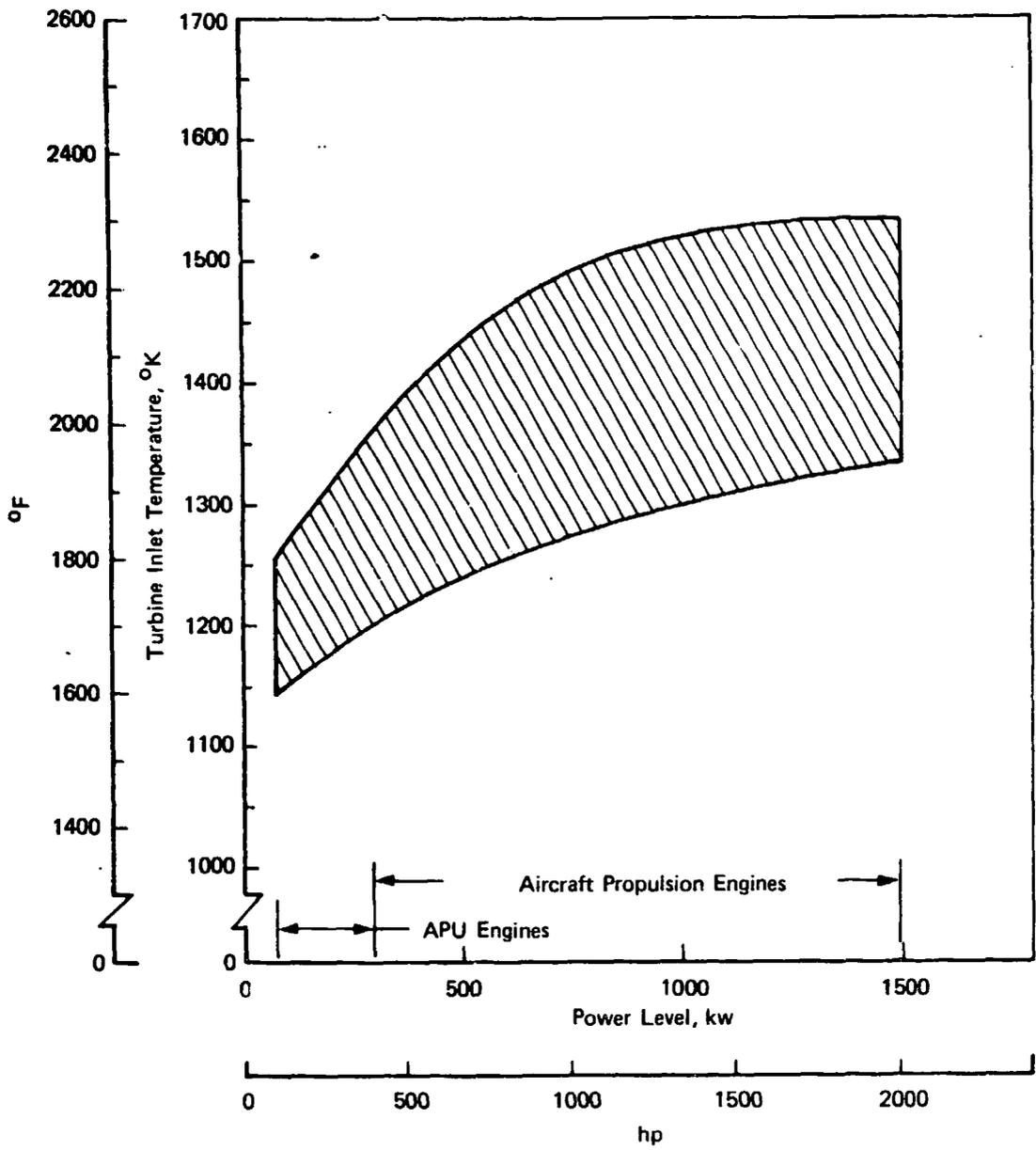


Figure 4. Range of turbine inlet temperature in current engines.

The data on turbine inlet temperature and pressure ratio for currently available engines show that both tend to increase significantly with horsepower. The observed trends are a direct illustration of the effects of size-related factors on achievable performance. The variation in cycle parameters with size indicates that although engine technology has advanced rapidly, the design philosophies utilized in the development of small engines can be quite different and can require several different configurations based on size and application.

III.4 Design Considerations for Different Small Turbine Applications

Table II shows how the design considerations differ depending on engine application. For example, helicopters operate at high power levels for long periods of time and incur many low-to-high power cycles. Operation is also often off-shore; therefore, reliability and durability are very important. Commuter aircraft, on the other hand, require lower average power and far fewer engine cycles; fuel economy, however, is extremely important. Agricultural aircraft require the capability to use heavier fuels. These three missions, therefore, require very different engine design approaches. Other applications further expand the range of required turbine operational capabilities.

III.5 Combustor Requirements

The design of a gas-turbine combustor is a complex process in which a wide range of conditions must be satisfied. Since these conditions are by no means compatible, a successful design involves reaching the most effective compromise among them. Although the relative priorities depend on the particular applications being considered, the general characteristics required of all combustors are as follows:

- Reliable and smooth ignition, including the capability for relight at altitude.
- Stable and complete combustion over a wide range of operating conditions (fuel flow and air temperature).
- Durability of the combustor hardware for specified exit temperature through adequate liner cooling.
- Uniform distribution of exit temperature (low value of exit pattern factor).
- Low emissions of smoke and gaseous pollutant species.
- Negligible deposition of coke on interior surfaces.
- Size and shape compatible with available space envelope.
- Ease of maintenance.
- Reasonable cost.

TABLE II. - DESIGN CONSIDERATIONS FOR SMALL AIRCRAFT
GAS TURBINE ENGINES

Application:	Commuter	Business	Agricultural	Helicopter	Drones, Missiles	APU
Type:	Fan or Prop	Prop or Jet	Prop	Shaft	Fan or Jet	Shaft
Power Range, kw:	450-1490	450-1490	370-745	300-1490	-	20-110
Fuel Consumption	•	•			•	•
Heavy Fuel Capability			•			
Specific Power			•	•	•	
Reliability under Cycling	•	•	•	•	•	•
Durability	•	•	•	•		•
Low Frontal Area	•	•			•	

There are a number of aspects unique to small combustors which make the achievement of these requirements more difficult than in larger configurations. For example, proper fuel distribution can be difficult as the combustor size is reduced because the number of nozzles per combustor is decreased (due to lower limit on orifice size). The increased surface-to-volume ratio of very small combustors leads to heat transfer and emissions (CO quenching) problems.

Different combustor design considerations are given special emphasis for each engine application. For example, the commuter aircraft requirement for low fuel consumption places the combustor design emphasis on liner cooling and traverse quality. The heavy fuel capability of agricultural engines places the combustor emphasis on fuel distribution and ignition.

The particular problems encountered in current small-combustor designs and the approaches used in resolving them are discussed in more detail below.

III.6 Flowpath Geometry

The size and shape of the space into which the combustor must fit is dictated by the dimensions and orientation of the surrounding turbomachinery. Since the last stage of compression in small engines is invariably a centrifugal compressor, the outer diameter of the combustor space envelope is usually fixed by the radial diffuser. The inner diameter, governed by the first stator row of the turbine, is generally on the order of a few inches below this value. The transition of the flow from the upper to the lower diameter must be accomplished within the combustor. The length available is constrained by the desirability of maintaining the axial distance between compressor and turbine at a minimum so as to avoid the stability problems associated with excessive shaft length.

From the standpoint of the combustor designer, an ideal configuration is a single-can combustor. This has the advantages of single-point fuel injection, minimum liner surface area to cool, and simple geometry. The basic drawback is the difficulty of interfacing the cylindrical combustor geometry with the annular flowpath geometry of the compressor and turbine. This results in an awkward and large overall engine configuration. A related problem is the difficulty of cooling the rather complex transition piece between the combustor and the turbine. One method of alleviating the transition problem is to mount the combustor on the centerline at the rear of the engine in a reverse-flow arrangement such as in the T63, for example. This approach, however, has not gained wide acceptance. The single-can combustor remains a concept used primarily in applications such as APU's where turbine inlet temperatures are modest and a compact engine shape is not a critical requirement.

Another fairly common type of combustor geometry is the slinger-based radial configuration. This is primarily used in low-power applications (below about 300 kw), but is also encountered in some medium-power engines. The principal advantage of the slinger approach is that it allows the use of a single injector while retaining the overall annular nature of the flowpath. This is achieved at the expense of a relatively complex "kidney-shaped" liner geometry which presents a considerable design challenge. The attendant problems include shaft sealing, liner cooling, and routing of air to the back face of the liner. The slinger configuration is of importance, however, because it offers what is often the only practical solution to the problem of circumferential fuel distribution in cases where a more conventional annular geometry with multiple injectors is not feasible.

The axial-flow annular combustor, conventionally used in large engines, has a number of features which make it a desirable configuration in cases where it can be applied. A major advantage is that it is relatively easy to cool because of its simple liner shape and characteristically smaller surface area. This generally allows operation at a higher temperature level with less cooling air than alternative geometries. Another advantage is the basic simplicity of the straight-through airflow path. This reduces the difficulty of a number of design problems such as, for example, flame stabilization. In most cases, however, the length available for the combustor precludes the use of this type of configuration. A notable exception is the T700 engine where a design approach has been utilized which alleviates the shaft stability problem and allots sufficient length for an axial-flow annular combustor.

The combustor geometry most compatible with the geometric constraints of the small engine flowpath is the reverse-flow annular configuration illustrated schematically in Figure 5. Other advantages of this configuration are the ability to make optimum use of the available combustion volume and simpler maintenance due to the accessibility of the fuel injectors. Its principal disadvantage is the relatively high surface-to-volume ratio inherent in the reverse-flow shape which makes liner cooling a difficult problem. Because of its generally desirable features, the reverse-flow annular is the combustor configuration predominantly used in current-day small engines in the mid-to-high power range.

III.7 Fuel Injection and Distribution

One of the most critical problems in the design of small combustors is to achieve a sufficiently uniform circumferential distribution of fuel with a small number of injectors and without seriously compromising ignition performance, flame stability and combustion efficiency. Uniformity is important because a poor temperature profile leaving the primary zone is a major factor contributing to an unsatisfactory combustor exit traverse quality. In addition, nonuniformities in the primary zone fuel/air distribution lead to excessive smoke formation and coking of interior surfaces.

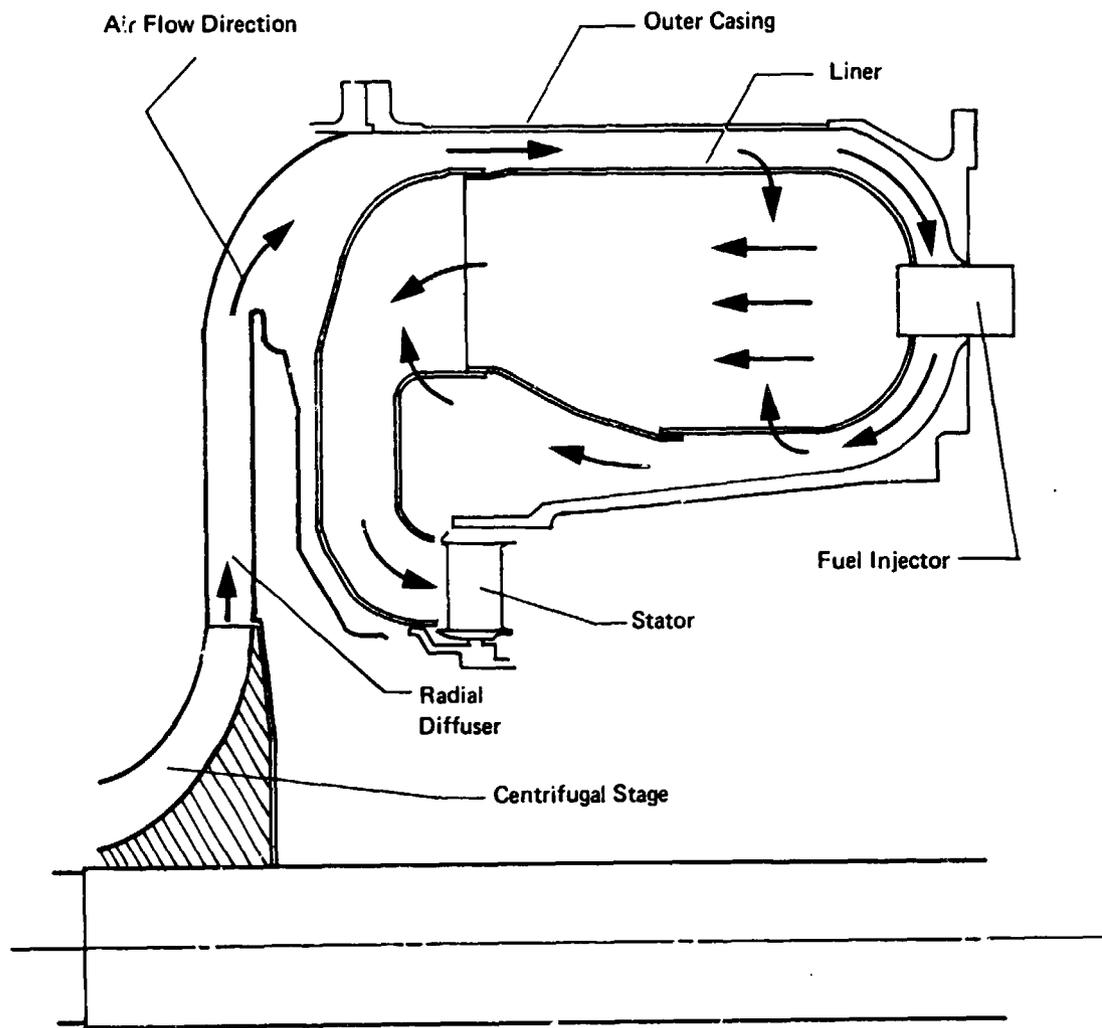


Figure 5. Illustration of a reverse-flow annular combustor configuration.

Ideally, one would like to select a number of fuel injectors so as to achieve a 1/1 ratio of injector spacing to annulus height as illustrated in Figure 6. This is seldom possible in small combustors because the required fuel flow per injector would be too low for adequate atomization with conventional pressure atomizers. The deterioration in atomizer performance as flow is reduced is illustrated by the typical curve shown in Figure 7 for an injector of about the minimum practical orifice size. Under conditions where fuel evaporation is the rate-controlling step, Ballal and Lefebvre (ref. 9) have demonstrated that combustion efficiency varies inversely as the 1.5 power of mean drop size. The increase in drop size with decreasing flow rate then often results in unacceptable combustion efficiency and stability at low-power conditions such as idle. Consequently, a design goal common to all small combustors is to reduce the number of fuel injectors. An incentive in addition to alleviating the atomization problem is the resulting decrease in the overall complexity and cost of the fuel system.

Another aspect of the fuel injection problem is the difficulty of achieving reliable ignition. The importance of atomization has been demonstrated by Ballal and Lefebvre (ref. 10) who have shown that the minimum spark energy needed to ignite a turbulent heterogeneous flowing mixture is roughly proportional to the mean drop size to the 4.5 power. At startup the fuel flow rates are significantly lower than the lowest operating values for the engine. In most cases then, if the fuel were divided among all of the injectors, the atomization would be completely inadequate to achieve ignition. The conventional solutions include separate primer nozzles, staging of fuel flow to the main injectors so that only a portion operate at startup, and piloted or dual-orifice atomizers. The ignition problem is particularly severe for injectors such as airblast atomizers where sufficient atomization is not obtained until the air flow rate through the combustor reaches a high enough value.

A variety of techniques are available for achieving uniform circumferential fuel distribution and acceptable combustion performance. The following approaches, used either individually or in combination, are the principal ones encountered in current combustor designs:

- Injectors in which the atomization performance is comparatively insensitive to flow rate. A good example is the airblast atomizer which offers several advantages that make it one of the more important approaches used in recent designs. As noted above, one of its major disadvantages is relatively poor startup performance.
- Using a relatively large number of conventional injectors and staging the fuel so that only a portion are operating at low-power conditions. This is a viable method of achieving acceptable performance over the operating range of the combustor. Its effectiveness is demonstrated by the results of recent tests conducted at NASA-Lewis (ref. 11).

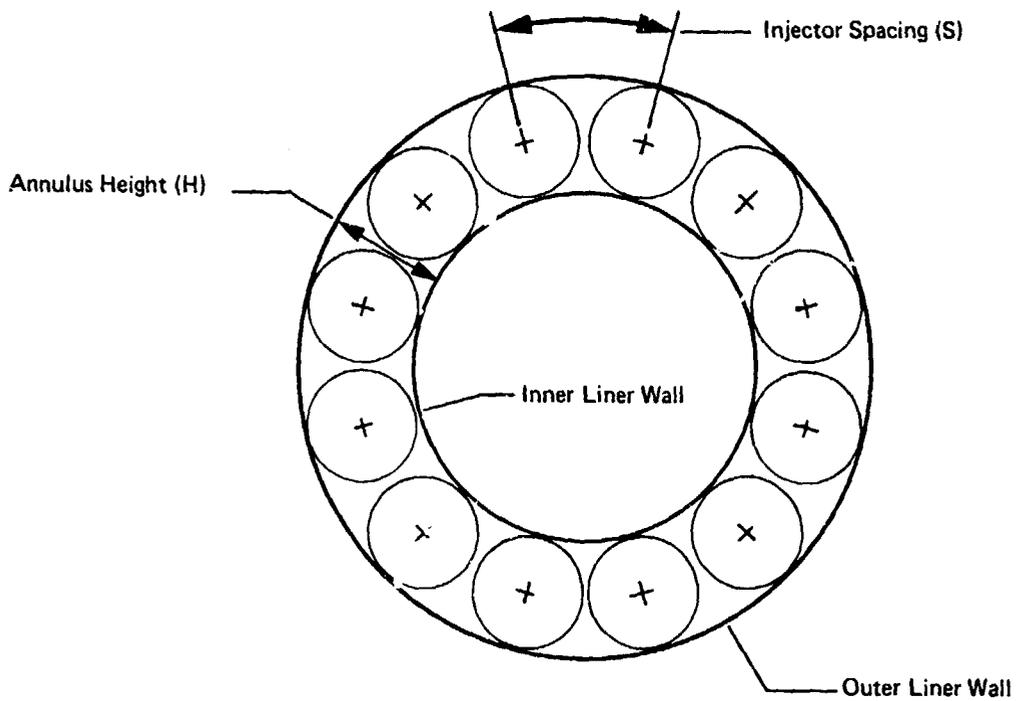


Figure 6. Optimum spacing of injectors for uniform circumferential distribution of fuel in annular combustor configurations.

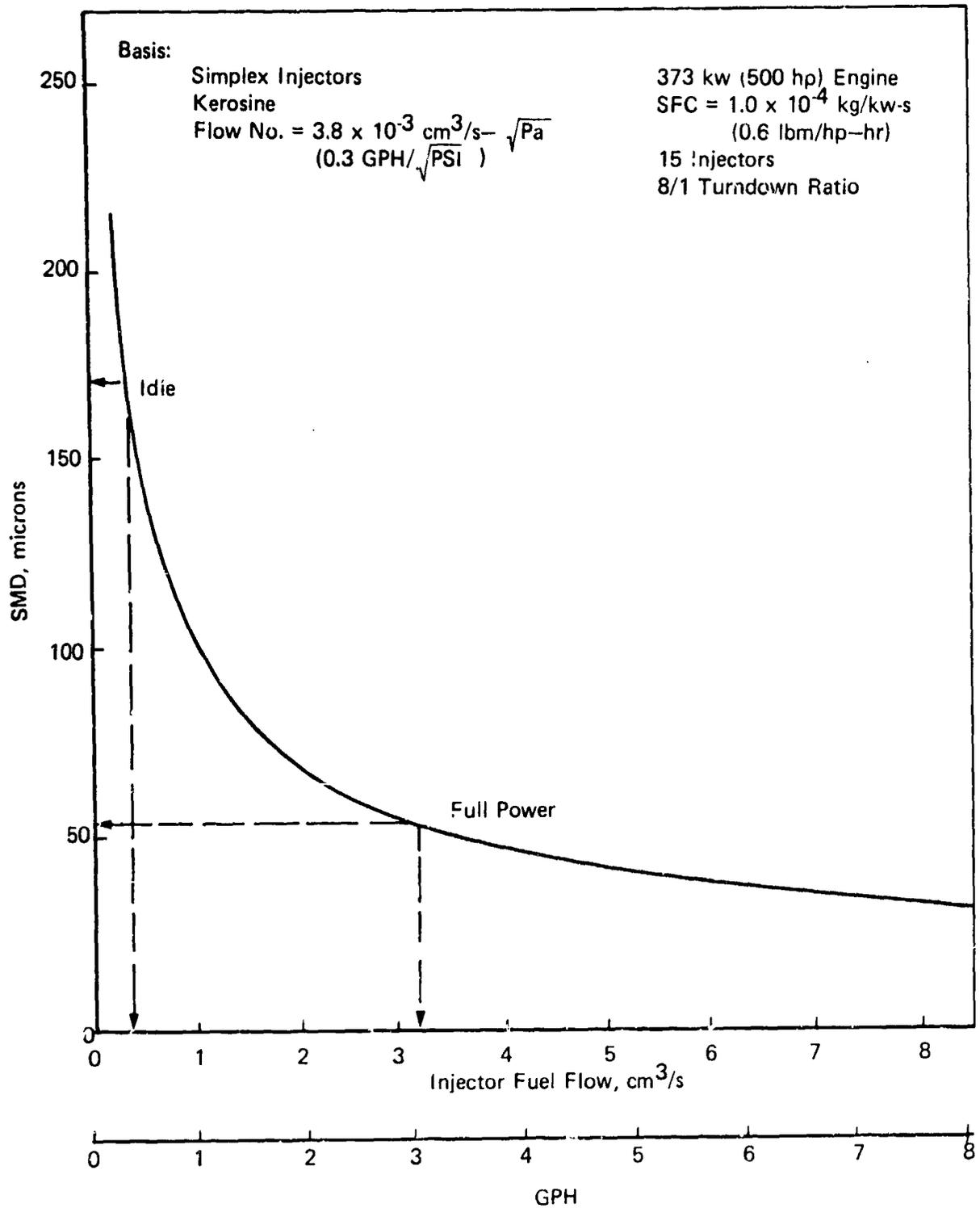


Figure 7. Illustration of how atomization performance deteriorates at low fuel flow rates.

- Atomizers designed to produce a flat spray. An example is the airblast concept described in ref. 12. This is a fairly recent development and, consequently, has seen limited application as yet.
- Injection of the fuel in a tangential direction. This approach has the advantage of simplicity and is used in many current designs. The principal difficulty lies in properly matching the injection angle to the primary-zone flow pattern.
- Retaining a high degree of inlet air swirl. Typical values are on the order of 30-40°. The overall swirling pattern of the flow acts to spread the fuel in the circumferential direction. The disadvantage is that the high degree of swirl increases the difficulty of achieving adequate flame stabilization.
- Tailoring of the primary zone flow pattern to produce "circumferential stirring" by a specific combination of a primary wall jet with individual groups of normal jets (ref. 13). This is a patented concept resulting in a horseshoe-shaped recirculation zone which is apparently successful in achieving uniform fuel distribution with a relatively small number of conventional atomizers.

The diversity of these approaches illustrates the difficulty of achieving an acceptable solution to the fuel injection and distribution problem inherent in small combustors.

III.8 Combustion Performance

The function of the primary zone is to stabilize the flame and achieve essentially complete combustion of the fuel. In a small combustor, this must be accomplished within an annulus which is on the order of 3.8-7.6 cm (1.5-3 inches) in height. Considering the classic PD scaling law, it is fairly obvious that it is inherently difficult to achieve acceptable combustion performance in small combustors, not only because of the size effect, but also because the pressure levels are characteristically lower than in larger engines. The problem is compounded by the quenching effect due to the relatively close proximity of the liner walls and their associated layers of film-cooling air. The influence of film-cooling on combustion efficiency is particularly important in small combustors because their characteristically high surface-to-volume ratio requires that a relatively large amount of cooling air be used. Another factor of concern is that the entering flow from the centrifugal stage often has a relatively high degree of swirl which makes it somewhat more difficult to obtain a satisfactory airflow pattern within the combustor.

The current approaches for primary-zone design in small combustors are essentially modifications of those conventionally used in larger configurations. In most cases, there is sufficient space available in reverse-flow configurations to design for a relatively low reference velocity on the order of 12-18 m/s (40-60 ft/s) so as to improve stability. Heat release rates of about 600 J/N-m³-s (6 x 10⁶ Btu/hr-ft³-atm) are typical (ref. 8) and values as high as 1500 J/N-m³-s (15 x 10⁶ Btu/hr-ft³-atm) and above are achievable with current technology, particularly in geometries other than reverse-flow annular.

The flow recirculation in the primary zone is established through variations of conventional techniques using secondary jets and/or dome swirlers. In the reverse-flow annular configuration, it is difficult to balance the air penetration through the inner and outer walls of the combustor. Consequently, it is not a simple task to obtain the double-vortex symmetric pattern normally achieved through the use of opposing rows of jets which is desirable from the standpoint of stability and mixing. The typical compromise is to settle for a single-sided air entry producing a single-vortex flow pattern in the primary zone.

Another variation encountered in small combustors is the use of the combustion air to supplement or supplant the film-cooling in the primary zone. This is accomplished by introducing the air as a wall jet directed so as to flow along the inside of the liner before entering the recirculation zone. The advantage of this approach is that it minimizes the adverse effects of film cooling air on combustion efficiency and temperature uniformity.

The proper design of the primary zone in a small combustor requires a careful integration of the fuel injection process with the air flow pattern so as to satisfy simultaneously the many conflicting requirements. Although useful guidelines exist, there is as yet no well-established methodology whereby this can be accomplished in a straightforward manner. The small-combustor designer must then rely on individual ingenuity in reaching an effective compromise. The resulting diversity in approaches is indicative of the lack of basic understanding of the primary zone and the severity of the problems which must be faced in obtaining satisfactory combustion performance.

III.9 Emissions Considerations

Turboprop engines below 2000 kw (Class P2) are not currently subject to emission constraints, because the emission impact of general aviation airports is relatively low, and the emission control costs per ton of pollutant are relatively high, particularly for small engines. Small combustors inherently produce relatively high emissions, because of higher surface area, less advanced injectors, and less-uniform fuel distribution. In 1973 the EPA had proposed standards (subsequently withdrawn except for smoke), for Class P2 engines as follows:

UHC	0.83 mg/kw-s (4.9 lb/1000 hp-hr)
CO	4.53 mg/kw-s (25.8 lb/1000 hp-hr)
NO _x	2.18 mg/kw-s (12.9 lb/1000 hp-hr)
Smoke	50 smoke number

Compared to the standards set for the larger T2, T3, T4 classes of engines, these were about a factor of 5 lower for gaseous emissions and a factor of 2 lower for smoke.

The idle emissions of current turboprop engines would have had to be modified had the standards not been withdrawn in March 1978. Figure 8 illustrates this point by showing the CO/NO_x emission characteristics of fifteen typical turboprop engines before and after modifications (refs. 14, 15). The observed tradeoff between NO_x and CO emission is characteristic of most combustion systems because NO production is promoted by high temperature combustion conditions which minimize CO.

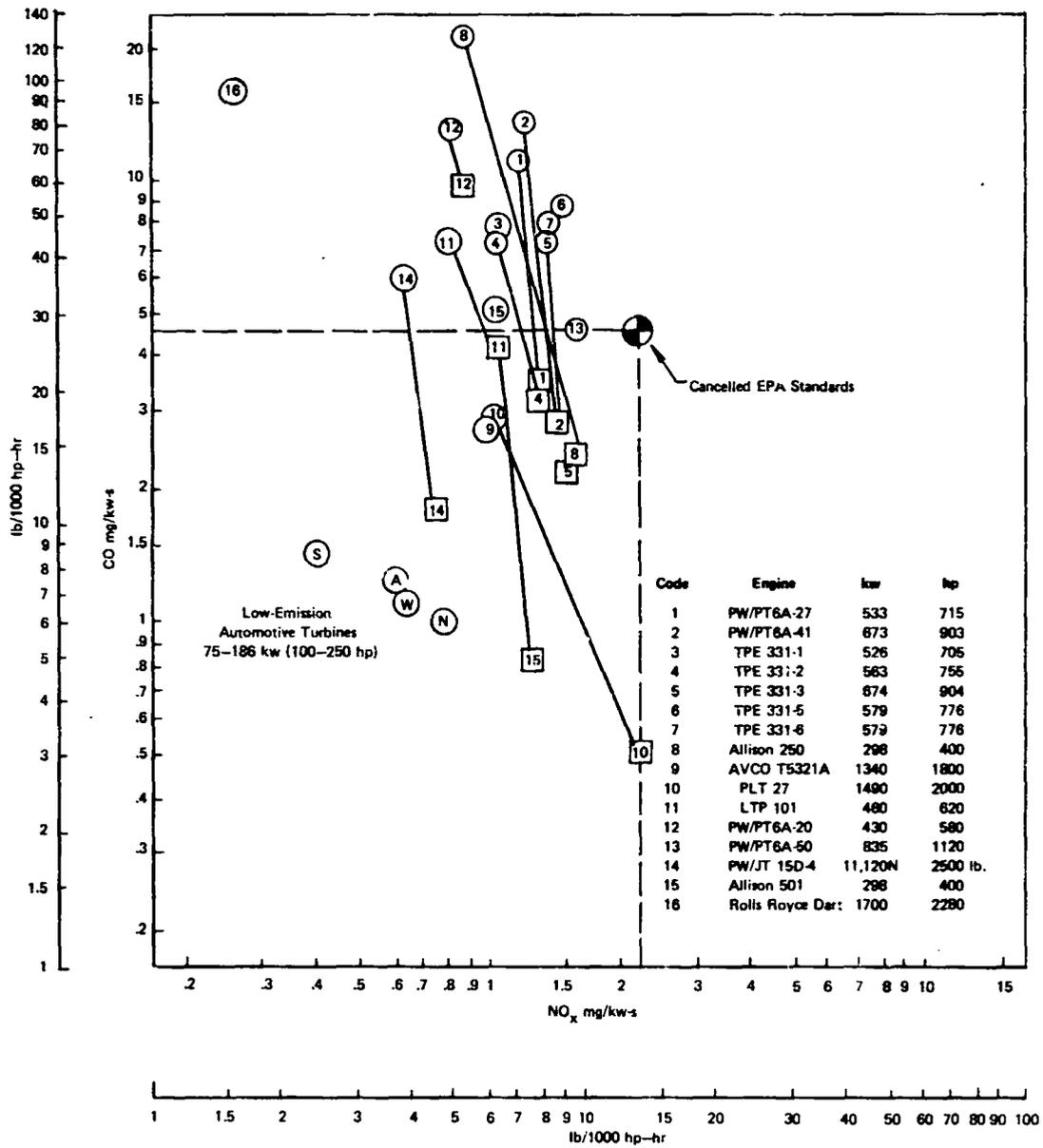
It is conceivable that emission requirements for small gas turbines might surface in the 1980-1990 time frame due to either (a) the short-term ambient standard or (b) the need to control NO_x or smoke for unconventional fuels. Substantial emission control technology has been developed already, and can be applied as necessary (at added cost) to meet future emission requirements. As shown in Figure 8, it seems reasonable to assume that most turboprop engines could be (or have been) modified if necessary to meet any reasonable future emission targets. Advanced emission-control technology is also potentially available from ongoing efforts in the automotive gas turbine area. Consequently, with the exception of smoke which remains a problem in small engines, emission control does not appear to be a major issue of concern.

III.10 Exit Temperature Profile

The function of the dilution zone in a combustor is to mix in the air remaining after combustion and cooling requirements have been met and achieve a uniform distribution of temperature in the exiting gas stream. Temperature uniformity is of critical importance because of its major impact on allowable turbine inlet temperature and hot-end durability. The parameter conventionally used as a measure of the overall nonuniformity of the gas stream leaving the combustor is the exit traverse quality defined as:

$$TQ = \frac{T_{\max} - T_m}{\Delta T}$$

where T_{\max} is the maximum measured value of temperature, T_m is the mean value, and ΔT is the temperature rise in the combustor. In addition to providing a low traverse quality, the combustor designer is faced with



Source: Refs. 14,15

Figure 8. Emissions for typical turboprop engines.

the task of specifically tailoring the radial temperature profile to match the requirements imposed by blade-stress considerations in the first stage.

Achieving an acceptable distribution is particularly important in small engines because they are generally uncooled and, therefore, less tolerant of deviations in temperature profile. This presents an especially severe problem in small combustors for several reasons:

- Because of the inherent difficulty in distributing the fuel circumferentially, the temperature distribution leaving the primary zone is nonuniform. As a result, the overall task which the dilution zone must perform is considerably increased. This is the principal cause of poor traverse quality in small combustors.
- The amount of dilution air available is generally low. This is due to the more severe cooling problem in small combustors which requires a proportionately greater use of cooling air.
- In the reverse-flow annular configuration, the flow in the transition piece is accelerating. Evidence suggests that this reduces the rate of spreading and mixing of the dilution jets.
- Due to the particular geometry of the reverse-flow configuration, some of the dilution occurs in a converging curved duct. This offers some advantage in trimming the radial profile. However, the flow is more complex and unpredictable than in conventional geometries. This aggravates the problem of optimizing the design of the dilution zone.

The approaches for obtaining acceptable dilution performance in small combustors are basically the same as the conventional ones used in larger configurations; that is, introducing the dilution air through one or more rows of circular holes in the liner walls sized so as to optimize the penetration and mixing. The amount of dilution air available is dependent on the particular design approach utilized. Typical values fall in the range of 20-40 percent of the total combustor air flow. The traverse quality achieved is generally on the order of 0.2 although values as low as 0.12 have been quoted. Because of the importance and severity of the problem, a considerable fraction of the combustor development effort is devoted to achieving an acceptable traverse quality.

III.11 Liner Cooling

In order to achieve sufficiently long life, the combustor liner must be kept at an acceptable temperature level. For conventional liner materials, the design metal temperature is typically on the order of 1090-1140°K (1500-1600°F). Maintaining this temperature level is an extremely difficult task in small combustors. This is primarily due to the characteristically high surface-to-volume ratio. In addition, practical limitations on cooling slot dimensions compromise the film-cooling effectiveness and consistency of performance which can be achieved with conventional approaches. The problem of liner cooling is particularly severe in the case of the reverse-flow annular configuration because of the curved wall in the transition section and the comparatively large total surface area which must be cooled.

The approach predominantly used in present-day small combustors is impingement film cooling. At a number of axial locations, the cooling air enters the liner through a row of small-diameter holes. The air jets impinge on a cooling skirt which then directs the flow so as to form a film along the inside of the liner wall. In some regions, convective cooling is provided as a supplement to the film cooling. The total amount of cooling air required depends significantly on a number of different factors, particularly pressure level. Typical values, however, are in the range of 30-50% of the combustor airflow.

Reducing the amount of cooling air required is desirable for several reasons, an important one being that this would make available more dilution air and simplify the task of achieving an acceptable traverse quality. There are various advanced concepts which show promise of making more effective use of the cooling air. These include Lamilloy, transpiration cooling, and augmented backside convection (ref. 16). Of these, the use of Lamilloy is in an advanced state of development and has shown the potential of reducing the required amount of cooling air by as much as 50%. All of the techniques, however, suffer from problems of varying degrees of severity. These are related to structural complexity, cost of fabrication, and long-term durability.

An alternative to increasing the efficiency of cooling techniques is to use protective coatings or liner materials which allow operation at higher temperatures. Coatings are used to a limited extent in troublesome regions of existing combustors. Candidates for liner materials which are under consideration include carbon/carbon composites, ceramics, and alloys of high-temperature materials such as columbium. Techniques for utilization of these materials are in varying stages of development, none sufficiently advanced for routine use in conventional present-day combustors.

III.12 Design Methodology

The procedures utilized in the design of combustors represent a mix of rules-of-thumb, empirical correlations, and computerized 2-D and 3-D flow models. In the past the principal reliance has been on correlations developed on the basis of the large backlog of data and experience obtained with large combustors. Application of these design correlations to small combustors suffers somewhat from the fact that they do not properly account for a number of important size-related effects.

Recent years have seen an increased development and utilization of sophisticated analytical models. The latest advance in this area is the computer model for small combustors developed by Bruce, Mongia, and Reynolds for Ft. Eustis (refs. 17, 18, 19). Although results have been encouraging, all of the available models have a number of deficiencies which prevent their routine use as effective design tools.

III.13 Development Considerations

Test-bed development presents a unique problem because of the small flowpath dimensions. Conventional probes are large in comparison to these dimensions and represent a significant blockage of the flow. This often leads to serious inaccuracies in the diagnostic measurements of flow details which are an integral part of the overall development process. The situation is further aggravated by the considerable unit-to-unit performance variations encountered in small combustors (refs. 11, 14). These size-related variations are due to the fact that the inevitable fabrication tolerances correspond to a considerable fraction of the overall dimensions in small combustors. The net result of these effects is to further complicate the already difficult task of combustor development.

IV. PROJECTED FUTURE REQUIREMENTS

IV.1 Major Influencing Factors

An expanding market is foreseen for small turbine engines in the next decade. For example, sales of current design turboprops are expected to grow at a rate of 7-10% a year, and turbojet/fan aircraft at 4-6% a year through 1982.*

The expected growth of the commuter airline market with its needs for a larger aircraft class (40-50 passengers) than currently available in general aviation should further increase sales. The engines for these aircraft will tend to be in the over-1120 kw (1500 hp) category, but may be growth versions of the smaller engines utilizing advanced technology to develop more power from a given core size.

Another potential new application, as mentioned previously, is the single and small twin engine, non-executive type aircraft. Engines for these aircraft are 190-450 kw (250-600 hp); overall research and development needs in this area were addressed in the NASA GATE studies (refs. 5,6,7,8). This "very-small-engine" technology will probably be shared somewhat by vehicular ground propulsion: first trucks and buses, and then automobiles.

Near-term development of small gas turbines will not center on increasing operational limits (altitude, specific power, speed, etc.), but will concentrate on expanding the breadth of the market and improving performance parameters such as specific fuel consumption, fuel flexibility, ease and economy of maintenance, and long life. Since first cost is the primary barrier preventing the utilization of gas turbines in the lower power categories, a concentrated effort aimed at cost reduction is expected. Also, because fuel costs and availability are becoming increasingly important concerns to current turbine operators, better fuel economy and the ability to operate on alternative fuels will be emphasized, especially in the higher power categories.

IV.2 Overall Engine Trends

The next decade should see increases in engine cycle pressure ratio and turbine inlet temperature, as shown in Figures 9 and 10. Greater increases are possible in the larger size small engines (1120-1490 kw, 1500-2000 hp) because of larger core airflows and flowpaths. Because of cycle requirements, turbofan engines will tend to be at the upper boundary of these curves. A specific fuel consumption of 0.68×10^{-4} kg/kw-s (.40 lb/hp-hr) is seen as a reasonable goal for engines in the 450-1490 kw (600-2000 hp) category; 0.76×10^{-4} kg/kw-s (.45 lb/hp-hr) is realistic for smaller engines. Advances beyond this

* ADL projections.

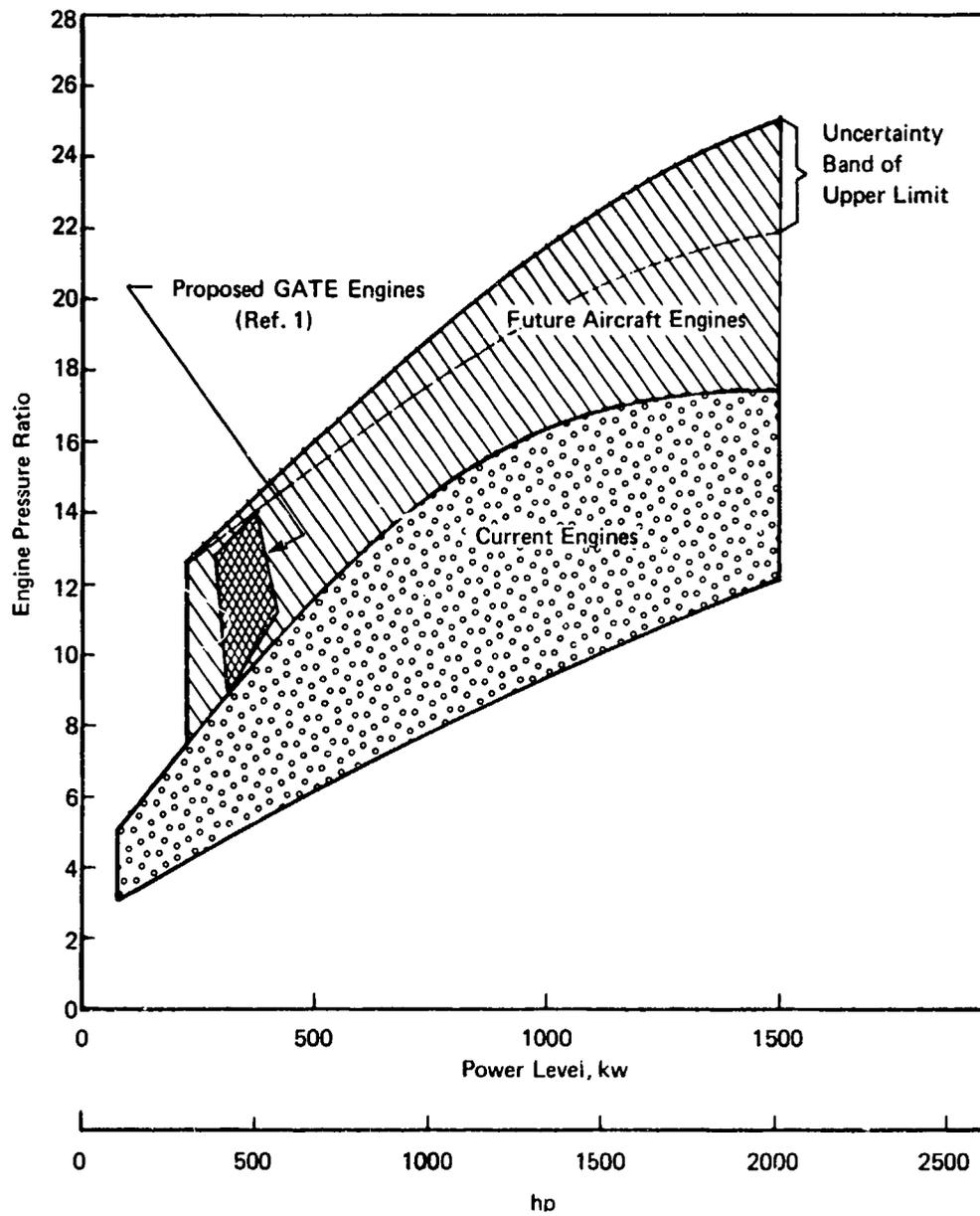


Figure 9. Projected trends in pressure ratio.

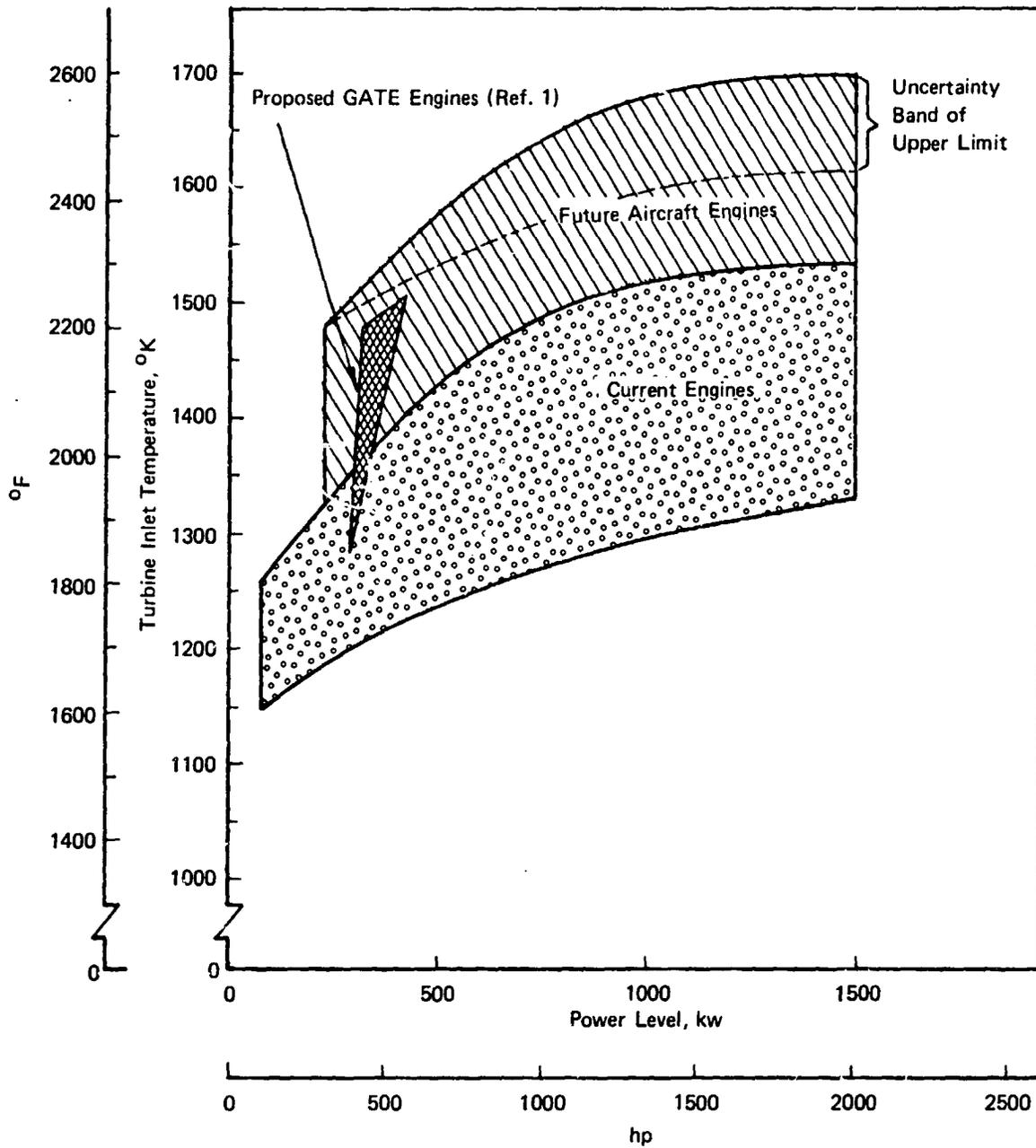


Figure 10. Projected trends in turbine inlet temperature.

will require radical new designs such as the incorporation of ceramic hot section components or the use of regenerative cycles. It is not expected that ceramic components will see widespread usage in manned aircraft during the next decade.

Regenerative cycles show promise for increasing the efficiency of the less-than-300 kw (400 hp)-class engines that are constrained to relatively low pressure ratios and turbine inlet temperatures. Since these engines will be competing against reciprocating engines with very low SFC's, the regenerative cycle may provide the means of providing near comparative performance. However, projected cost is high and significant research and development will be needed to produce a viable regenerative small engine. This development is not expected to occur in the next generation of engines.

Pressure ratios should edge up to an industry average of over 10/1 with increases in efficiency in high-pressure centrifugal compressors and diffusers. Turbine inlet temperatures will more frequently exceed 1370°K (2000°F), especially in the higher power engines, requiring high-pressure turbine stator cooling and, in some applications, rotor blade cooling. Therefore, specific power will increase. However, a very serious effort will be necessary to implement these improvements at reasonable cost, and to maintain reasonable life and maintenance costs for the hot section.

If full-scale development is initiated in the near future on small (190-450 kw) (250-600 hp) engines, first-cost considerations will dominate the design approaches. Difficulties associated with the design of very small flowpaths will probably lead to conservative engine aerodynamic and thermodynamic designs, with development of new manufacturing techniques being of primary importance. It is expected that the SFC of these first generation small engines will not be competitive with reciprocating engines. However, other factors such as safety, reliability, low noise, and long life could still provide lower life cycle costs than reciprocating engines.

Current small gas turbine engines are not tolerant of substantial deviations in fuel properties. The standard fuel is typically a low-boiling-range distillate oil with relatively low aromatics (10%), relatively high hydrogen content (C/H = 6.1), and essentially no bound nitrogen. These properties are conducive to evaporation, ignition, and combustion of the fuel in small combustors with low smoke, tolerable heat flux, and low NO_x.

In the future, there will be economic incentives to use less refined fuels in gas turbine engines. The properties of future fuels are obviously a matter of speculation; however, those listed in Table III (ref. 20) are under consideration. The major trends in fuel

TABLE III. - LIQUID FUELS SPECIFIED FOR
STATIONARY GAS TURBINE ENGINES (1973)

<u>Fuel</u>	<u>Number of Engines</u>
Light Distillate	899
Kerosine	8
Heavy Distillate	10
Crude Oil	46
Residual Oil	85
Blends	14

Source: ref. 20

properties are to higher C/H ratio, higher fuel nitrogen, higher viscosity, and higher aromatic content.

Stationary gas turbine engines which have a higher duty cycle (1000 - 4000 hr/year) and thus an even greater incentive to utilize lower cost fuels, already burn various alternative fuel oils, as shown in Table III. However, these engines at 7450-74,500 kw (10,000-100,000 hp) output have less severe design requirements because they are not required to be airborne. The small aircraft combustor of 300-1490 kw (400-2000 hp) output will be considerably more difficult to adapt to less refined fuels.

IV.3 Relationship Between Engine and Combustor Requirements

The previous section outlined the various problems which are encountered in the design of present-day small combustors. All of these are reimportant to varying degrees and deserve attention in future R&D efforts. In order to establish the appropriate priorities, however, we need to identify those problem areas whose severity is expected to increase with the projected changes in overall engine requirements. These represent the major hurdles which, unless overcome, may limit or prevent the achievement of the desired advances in small-engine technology.

Figure 11 presents a schematic illustration of the projected engine trends and the manner in which they impact on future combustor requirements. The anticipated increases in pressure ratio and turbine inlet temperature in response to demands for better fuel economy will have a major influence on the increasingly important issue of durability. From the standpoint of the combustor, this primarily means devising more effective methods of liner thermal design in order to achieve acceptable life under the more severe operating conditions.

Durability will also be affected by the broader fuel specifications which future engines will have to tolerate. In addition, the expected deterioration in fuel properties will have a significant impact on atomizer performance and circumferential fuel distribution requirements.

The potential development of new low-cost high-efficiency engines for the low-power end of the general-aviation market is a special case. Because of the high risks involved, it is our perception that rapid progress in this area will not occur without significant government support. If engines in this category are to be developed, the impact will be felt in essentially all aspects of combustor design and performance. The principal effect, however, will be on the requirements in terms of fuel injection and distribution. Viable solutions may well require a departure from the more conventional flowpath geometries.

Based on an assessment of the opinions expressed by the different organizations participating in the study, we feel that the major area of concern is in achieving acceptable hot-end durability. Improvements

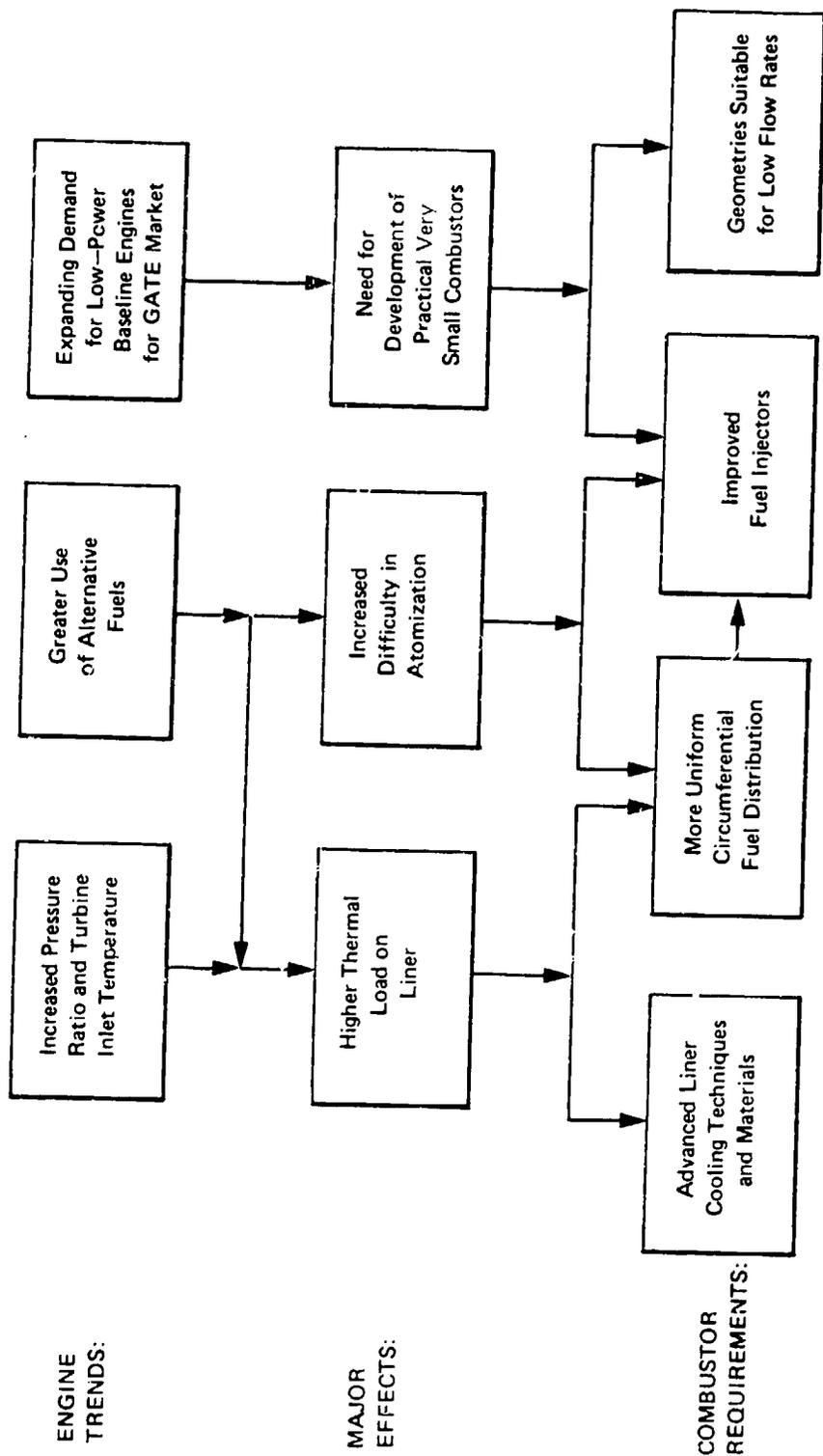


Figure 11. Impact of engine trends on future combustor requirements.

in this area would be necessary even if the status quo in overall engine requirements were maintained. The fact that the combustor operating environment is becoming more hostile, aggravates the basic problem. Although other aspects are important in their own right, a major part of the difficulties encountered is related to the compromises necessary to insure durability. The specific trends in combustor requirements which we foresee as assuming major importance are described below.

IV.4 Fuel Flexibility

The small gas turbine combustor has perhaps the most ambitious design objectives of all combustion devices. It has roughly the same small size and extremely high combustion intensity as the modern diesel engine chamber and has the additional requirement that it must withstand continuous heat flux. The selection of fuel type has until recently been a simple matter of finding the most refined light distillates available from the refining of crude oil (Avgas, JP-4, etc.). The decreasing availability and rising prices of these light distillates will increase the desirability of shifting to alternative fuels. Although it is difficult to predict the specific fuels which will be used in future years, the likely trends in characteristics, as illustrated by the data given in Table IV, are fairly certain. The key properties and their anticipated effects on the combustor can be summarized as follows:

- Higher C/H ratio, which promotes smoke and increased heat flux to the liner.
- Higher fuel nitrogen, leading to NO_x-control requirements.
- Higher aromatics, leading to increased smoke and PAH emissions.
- Higher viscosity, resulting in atomization difficulties.
- Lower volatility, requiring a reduction in mean drop size to achieve acceptable ignition and combustion efficiency.

As can be seen, the impact will be felt in virtually all areas of design and performance. It promises to be a substantial research and development effort, then to adapt the small gas turbine combustor to the use of less-refined fuels.

IV.5 Liner Durability

The thermal load imposed on the combustor liner is expected to increase dramatically due to the projected increases in operating pressure and temperature and the anticipated requirement for burning heavier fuels. The higher pressure levels increase not only the radiation within the liner, but also the temperature of the available cooling air. The heavier fuels increase radiation because of their greater soot-forming tendency which results from both poor atomization and chemical composition.

TABLE IV. - CHARACTERISTICS OF ALTERNATIVE FUELS

Fuel	(C/H) _{mass}	N	Viscosity 10 ⁻⁶ m ² /s	Aromatic Content	Cetane No.	T(10% Evap), °K	T(90% Evap), °K
Kerosine/JP-4	6.1	(negligible)	0.7	10%	50-55	~ 370	~ 490
#2 Diesel Oil	6.8 ± 0.2	0.1%	3	25%	50-60	500	590
Light Distillate (#2)	7.3 ± 0.2	0.2%	8	20%	30-40	~ 490	~ 590
Heavy Distillate (#4)	7.8 ± 0.2	0.3%	20 ± 10	-	-	490	640
Residual (#6)	8.0 ± 0.2	0.4%	200-1000	-	-	560	700
NASA future broad Spec. Fuel (1977)	6.80	(negligible)	15 max	35%	-	480	620
Shale Oil							
Raw Fuel Range Distillate	7.3 6.3	1.4% 0.1%	6 2	- 24%	- -	360 480	690 620
Tar Sands (Alberta)	6.9	0.1-0.5%	10-70	-	-	370	760
Coal Derived Oil							
Raw Syncrude	9.8	0.5%	6-15	55%	-	~ 480	~ 670
Hydrotreated	8.5	0.2%	3	42%	-	480	590
SRC-II (Gulf Middle Distillate)	9.5	1.8%	3.2	62%	< 20	470	530
MAJOR EFFECTS	<ul style="list-style-type: none"> ● Liner heat flux ● Smoke ● Flame temp. 	<ul style="list-style-type: none"> ● NO_x 					<ul style="list-style-type: none"> ● Atomization ● Evaporation ● Ignition, lean limit

In order to handle the greater thermal loads with conventional cooling techniques and liner materials, the amount of cooling air would have to be increased significantly. On the basis of a simplified analysis of available cooling experience curves (refs. 14, 17, 21) and data on alternative fuels (ref. 22), we estimate that the required increase would be around 50-70 percent of current levels. This represents what would be needed to counteract the combined effects of operating conditions and fuel properties which are roughly equal in magnitude. Such increases are impractical and will become even more so in the future because of a number of factors including the reduction in the total amount of available air associated with higher-temperature-rise combustors.

It is obvious that there will be a critical requirement for more efficient liner-cooling approaches. These should be capable of providing acceptable durability with significantly less cooling air. A reasonable target would be to reduce cooling-air requirements to about 50 percent of current levels. Techniques presently under development have demonstrated the potential of reaching this goal. However, further efforts in this area are necessary to solve a number of practical problems.

In order to supplement advanced cooling techniques, it would be desirable to develop high-temperature materials and coatings suitable for use in combustor liners. These materials will most likely be first developed and introduced in automotive regenerative turbines where the need is more immediate than that for aircraft engines. Subsequent utilization in aviation applications will result from technology transfer. The need for advanced materials is expected to become critical in future years as the combustor inlet temperature (and, consequently, the temperature of the available cooling air) continues to increase in response to the demand for greater cycle efficiency.

The increasing severity of the cooling problem will dictate changes in areas other than liner thermal design. For example, it is possible that there will be a greater incentive to use flowpath geometries, such as the axial-flow annular, which are easier to cool. It is doubtful, however, that the advantages of the reverse-flow annular geometry will be completely eliminated. Consequently, it will most likely continue to be the predominant combustor configuration in small engine applications. The principal differences in future designs will be a tendency to make the liner more compact in order to reduce the surface area which must be cooled.

The trend towards more compact liners will require that combustors be capable of operating at significantly higher values of heat release rate. This will be reinforced by the modest demand for operation at higher altitudes in low-power applications. The increase in heat release rate will have to be accomplished without compromising existing levels of stability and combustion efficiency. As alternative fuels

are introduced into service, there will be a tendency towards leaner primary zones in order to reduce smoke formation and radiation load. This will aggravate the problem of obtaining acceptable combustion performance. Consequently, optimizing the design of the primary zone in the future will represent even more of a challenge than it does in current combustors.

IV.6 Improved Fuel Injection and Distribution

Future combustors will be required to achieve better atomization and a significantly more uniform circumferential distribution of fuel in the primary zone for several reasons:

- To alleviate the anticipated increase in radiation load resulting from the use of alternative fuels and higher levels of pressure and temperature.
- To prevent deterioration in exit traverse quality which will assume greater importance because of increasing turbine inlet temperatures.
- To reduce the increase in smoke emissions associated with the higher aromatic content and C/H ratio of potential fuels.
- To achieve acceptable ignition with heavier fuels which are not easily atomized due to their higher viscosity.

The improvement in uniformity will require a more careful integration of the method of fuel injection with the primary-zone aerodynamics. An additional requirement will be the further development of suitable fuel injectors which are capable of providing good atomization over a wide flow range, a uniform and controllable spray pattern, and lower sensitivity to increases in fuel viscosity. In this regard, we see an increased role for atomizers of the airblast variety whose inherent characteristics are well-suited to satisfying these needs.

IV.7 GATE Combustors

If the anticipated development of engines for the GATE market becomes a reality, there will be a requirement for combustor configurations suitable for relatively low flow rates. This application area falls in a region of power level where the use of multiple-injector configurations such as the reverse-flow annular starts to become impractical. Unless advanced methods of fuel injection are developed, alternative configurations, such as the slinger-based radial geometry, may offer the only viable solution. It is likely then that future years will see greater attention devoted to the further development of this type of configuration.

V. ASSESSMENT OF COMBUSTOR RESEARCH AND DEVELOPMENT NEEDS

V.1 Overall Goals

In order to provide the proper focus for identifying the research and development needs which must be addressed, it is worthwhile to consider the potential benefits we are trying to obtain and the effect of the combustor in achieving the desired goals. From the standpoint of the overall engine, the principal benefits which can be realized through research and development are as follows:

- Extended Operating Limits. There is no major pressure to extend mission envelopes beyond what is typical of current general aviation aircraft. A far more important factor which falls in this category is the requirement to increase the inherent fuel flexibility of turbine engines. The combustor is the key component in controlling the extent to which this can be achieved.
- Increased Operating Efficiency. This has always been a major objective in developing new aircraft engines because of the large leverage fuel economy exerts on total life-cycle costs (ref. 23). Rising fuel prices increase the importance of achieving low SFC. The combustor influences overall thermodynamic efficiency primarily in the extent to which its durability limits the allowable values of maximum cycle pressure and temperature.
- Greater Reliability. Safety is obviously a major concern in aircraft engines. As far as the combustor is concerned, contributions to improved reliability are achievable by reducing the complexity of the fuel injection system and designing the primary zone so that prompt ignition is obtained at the required altitude conditions.
- Increased Durability. As noted previously, hot-end durability is a critical issue whose importance will increase with time. Improving durability is an effective means of reducing life-cycle costs by extending the useful life of the engine and increasing the time between overhauls. The combustor aspects relating to durability are liner life and the effect of the exit temperature profile on the first turbine stage.
- Reduced Manufacturing Costs. The development of low-cost turbine engines is a requisite for achieving significant expansion in the low-power portion of the general aviation market. The combustor, however, has relatively little influence on first-cost of the engine, contributing only about 5-10 percent of the total. A major portion of this is associated with the fuel system hardware, principally the injectors. Unless advanced techniques for meeting future requirements are considerably more expensive than present, there seems to be little incentive to significantly reduce combustor costs other than by attempting to decrease the number of fuel injectors.

- Reduced Design and Development Costs. The contribution of the combustor to engine development costs is typically on the order of 15 percent. In recent years, considerably higher levels have been expended for the purpose of reducing emissions in anticipation of stringent standards. The future problems which will be encountered in small combustors may well be comparable in severity to the emission reduction problem, and comparable levels of development effort may be required. Consequently, there is justification for attempting to reduce the time, effort, and associated costs of combustor development.
- Reduced Maintenance Costs. As mentioned above, an effective means of reducing the total cost of maintenance is to improve engine durability. Another obvious method is to use a modular approach in the design of the overall configuration so as to simplify disassembly and maintenance when required. With regard to the combustor, this primarily affects the choice of flowpath geometry and the details of the methods used in the construction of the liner. These considerations are fairly specific to the geometric characteristics and constraints of each particular engine. Consequently, they are not well-suited to being addressed in a generalized manner other than as factors to be weighed in evaluating the relative merits of alternative design approaches.

In the remainder of this section, the specific needs which must be considered in pursuing the desired goals are discussed separately under each of the major technology areas related to combustor design and development.

V.2 Primary-Zone Design

The primary zone represents the most important portion of any gas turbine combustion system because of the many critical functions which it serves and because its performance affects virtually all aspects of combustor operation. Consequently, improvements in the general area of primary-zone design are a key to solving a number of the current and projected problems of small combustors. The overall advances required include the following:

- Improved ignition capabilities.
- Higher heat release rate and better mixing at high-power conditions.
- Higher combustion efficiency at low-power conditions.
- Improved part load performance.
- Reduced thermal load on the liner.

Although a variety of design concepts are available and in use in current combustors, there is none to our knowledge which is completely

successful in satisfying all of the conflicting requirements of the primary zone. As noted previously, this problem is expected to worsen in the future as requirements in terms of operating pressure and temperature levels, fuel/air uniformity, and heat release rate become more stringent. There is a need then for an advanced approach to primary zone design which is capable of meeting the desired goals.

The development of advanced concepts is hampered by the scarcity of analytical tools specific to small combustors. The available design correlations relating primary-zone performance to operating conditions and geometry have been developed mainly from data obtained with large systems. Many effects which increase in importance as the size of the combustion volume is reduced are not included. In addition, they are based on conventional air flow patterns and flame stabilization techniques which are not necessarily representative of those found in small combustors. The direct application of these correlations to small combustors leads to inaccuracies which must be subsequently corrected by costly trial-and-error development and/or to designs which are overly conservative. A comprehensive investigation of combustion performance in small combustor configurations is needed in order to assess the validity of existing correlations and develop new ones which provide a better understanding of the complex processes occurring within the primary zone.

A final need which falls in the category of primary-zone design is the further development of configurations suitable for use in low-power applications. Examples include single cans, widely spaced multiple cans, and slinger combustors. Of these, the slinger would appear to have the most potential. Due to the relative complexity of the flow path geometry imposed by the use of the slinger, the standard techniques for design of the primary zone cannot be applied directly. In addition, although the slinger is known to produce good atomization and a relatively uniform circumferential fuel distribution, established procedures for achieving a desired level of atomization performance do not exist. The overall design experience which is available resides primarily with those organizations that have concentrated on this type of combustion system. Because of the potential growth in importance of the slinger configuration in small-engine applications, an investigation of its unique design problems is justified.

V.3 Fuel Injection

A significant number of the problems encountered in small combustors can be directly related to the fuel injection process. In order to correct the various deficiencies in current injectors, advanced concepts are required which achieve significant improvements in the following areas:

- Atomization performance at low fuel flow rates.
- Spatial spray distribution characteristics.

- Plugging and coking tendencies.
- Multi-fuel capabilities.

A great deal of effort has been expended in the past in developing design correlations particularly for conventional swirl atomizers and, to a lesser extent, for atomizers of the airblast variety. Most of these correlations are based on data taken at ambient conditions and concentrate on predictions of mean drop size and size distribution. Relatively little information is available on atomization performance, particularly spatial distribution in the spray, at very low flow rates and elevated pressures and temperatures. As an aid to developing advanced injector concepts, there is a need for improved design correlations which provide a more accurate prediction of injector performance at conditions representative of the actual combustor environment.

V.4 Liner Thermal Design

The basic requirement in this area is to develop practical means of coping with the high thermal loadings associated with the projected increases in operating pressure and temperature levels and the future introduction of alternative fuels. Meeting this requirement will be a crucial step in insuring that the desired advances in small-engine technology can be achieved.

It is certain that small combustors will require methods of liner cooling which provide greater durability and more effective use of cooling air than present designs. A number of methods, which are currently under investigation, offer significant promise of achieving these goals. The chief drawback is that they are structurally complex. As a result, they are more difficult and costly to fabricate than conventional liners and are also more prone to reliability problems. Further development of the most promising available techniques is required in order to overcome the practical difficulties associated with their utilization.

As combustor inlet temperatures approach levels corresponding to regenerative conditions, a point will be reached where the temperature of the available cooling air is too high for conventional liner materials no matter how efficient the cooling technique. When this occurs, the only feasible method of addressing the problem of liner durability will be to use materials capable of operating at high temperature with little or no cooling. Considerable advances have been made in the technology of high-temperature materials. However, major problems remain to be resolved before it is feasible to use these materials routinely in aircraft combustors. The principal problems are related to fabrication, cost, structural integrity and oxidation resistance. The task of addressing these problems is hampered by a scarcity of information on the relevant properties and characteristics of the

existing candidate materials. There is a need for a concerted effort to develop suitable high-temperature materials to alleviate liner cooling problems in the near-term and to eventually eliminate the need for cooling in far-term applications.

V.5 Dilution-Zone Design

The higher turbine inlet temperatures in future engines will place a greater premium on achieving a uniform temperature in the gas stream leaving the combustor. In addition, the amount of dilution air available for profile trimming will generally be lower because of the higher overall fuel/air ratio and the increased demand for cooling air. Consequently, in order to maintain or improve on the current levels of pattern factor, advanced dilution techniques representing a radical departure from those approaches currently used, may be required.

The available correlations of dilution performance have been derived primarily on the basis of data on jet penetration and mixing in constant-area ducts with uniform upstream velocity and temperature profiles. The flowpath geometries used in small combustors are generally more complex. For example, a unique feature of reverse-flow annular combustors is a transition section consisting of a converging curved duct in which the flow is turned through 180°. In addition, the velocity and temperature profiles at the inlet are generally far from being uniform. Although the conventional correlations are useful in providing design guidelines, they are not representative of the actual flow situation in small-combustor configurations. Consequently, improved correlations are needed in order to meet the more difficult challenge anticipated in the design of the dilution zone in future combustors.

V.6 Modeling

Recent years have seen a rapid growth in the development and utilization of sophisticated computerized models for predicting the detailed performance characteristics of combustors. These models offer significant potential as tools to aid in the process of combustor design and development. A number of problems in the existing models must be overcome, however, in order for them to reach their full potential. Specifically, significant improvements are required in the following models:

- Fuel preparation.
- Primary-zone performance.
- Dilution-zone aerodynamics.
- Liner heat transfer.

The major deficiencies are in the areas of accuracy, calculation time, and ease of utilization by the designer.

Another need which falls in the general category of modeling is improved methods of predicting liner life. The current techniques for structural analysis of the liner and life prediction are unsatisfactory in a number of respects. One problem with available models is that they are costly and time consuming to implement. In addition, they do not provide an accurate representation of several factors of major importance in small combustors such as the effects of low cycle fatigue on liner life. As a result, considerable development time and effort is devoted to durability testing and correcting of structural problems.

V.7 Alternative Fuels

There is wide speculation as to the specific fuels which will be utilized in future aircraft turbine engines. Estimates range from a moderate broadening of existing fuel specifications to requirements for burning the more exotic coal-derived liquids. Although turbine engines are somewhat tolerant of variations in fuel properties, the extent is not known to any certain degree. The repercussions of burning fuels such as SRC-II and shale oil in small gas turbines can be partially anticipated, but some problem areas may be overlooked until actual tests are performed. There is a need to be more definitive in this critical area in order to assess the scope of potential problems and provide the necessary focus for the required research and development efforts.

The use of alternative fuels will impact on many aspects of combustor design. In order to anticipate and account for these effects in the design process, information is required on the relevant properties of potential fuels such as:

- Smoke and coke forming tendencies.
- Radiation characteristics.
- Kinetics and chemistry of decomposition, pyrolysis, and combustion.
- Atomization characteristics in conventional injectors.

Although a number of studies have been performed in these areas, the available information is sparse and not of a form readily useful to the combustor designer.

VI. SMALL-COMBUSTOR R&D PLAN

VI.1 Potential Programs for Addressing Needs

The major portion of the Small-Combustor Forum was devoted to identifying, discussing, and prioritizing the research and development programs which should be pursued in each of the combustor technology areas. This series of detailed discussions resulted in a total of 35 suggested programs. These are listed in Table V along with their priority ratings obtained by averaging the scores assigned to the individual programs by each of the organizations participating in the forum.

In the area of primary-zone design, the principal concern appears to be the lack of basic information and correlations specific to combustion performance in small-combustor configurations. Although there was general agreement regarding the necessity of conducting parametric experimental studies, it was felt that in order for the results to be widely applicable, the testing should be performed with one or more idealized reference configurations designed so as to eliminate unwanted geometric effects. Another important area of concern, illustrated by the second program listed, is the perceived inability of current primary-zone concepts to deal adequately with the unique combustion problems of small combustors.

The most critical requirement in the area of fuel injection was judged to be the development of advanced injector concepts with characteristics more suited to providing acceptable atomization performance at low fuel flow rates than currently available designs. Most of the remaining programs suggested relate to providing the information and tools needed to achieve the necessary advances in injector technology.

The crucial importance of durability as an issue is evidenced by the generally high priorities assigned to the programs in the category of liner thermal design. Although only three programs were suggested, the top two represent comprehensive efforts aimed at developing practical liner configurations and materials capable of withstanding the more hostile combustor environment anticipated in future small engines.

The programs identified in the area of dilution focus on the increasingly difficult task of achieving acceptable exit traverse quality. The efforts suggested address this problem primarily through the development of improved methods of dilution and the generation of useful design data and correlations specific to small-combustor flowpath geometries.

With regard to modeling efforts, the general consensus appears to be that the maximum benefit to the combustion community would be obtained by developing improved generalized submodels of the relevant phenomena and processes rather than a comprehensive integrated model of combustor performance. The principal requirements in this respect are in the

TABLE V. - LIST OF SUGGESTED R&D PROGRAMS				
Technology Area	Program Title	Priority Rating		Program Description
		Average Score ¹	Standard Deviation ²	
Primary-Zone Design	Parametric Investigation of Combustion Performance	1.8	1.3	Parametric primary-zone tests to generate data for derivation of correlations specific to small combustors.
	Advanced Primary-Zone Design Concepts	2.9	1.6	Experimental development of advanced concepts for improved combustion performance.
	Investigation of Slinger Combustors	2.4	1.6	Parametric tests to derive correlations of combustion performance in slinger combustors.
	Reference Primary-Zone Geometry	2.2	1.8	Development of idealized primary-zone combustor (e.g., well-stirred reactor) as baseline configuration for experimental studies.
	Investigation of Low-Flow Combustor Configurations	1.8	1.4	Parametric tests to generate design data and correlations for combustor geometries suited to low-power applications.
Fuel Injection	Advanced Injector Concepts	1.7	1.5	Development of injector concepts with characteristics matching unique requirements of small combustors.
	Injector Design Correlations	3.6	1.2	Parametric spray tests to develop improved correlations for advanced small injectors.
	Combination of Programs (a) and (b)	2.4	1.8	Described below.
	(a) Standardization of Spray Measurement Methods	2.4	1.1	Development of a standard technique for measurement and reporting of spray data.
	Combustion Effects of Spray Distribution	2.3	1.7	Tests in reference combustors to determine influence of spray distribution on combustion performance.
	(b) Review of Fuel-Preparation Technology	1.7	1.3	Study to assess the state-of-the-art in methods of fuel preparation (injectors and vaporizers).
	Advanced Vaporizer Designs	1.2	1.5	Development of improved vaporizer configurations.
	Effects of Spray on Noise	0.6	0.9	Tests to determine influence of spray distribution on combustion noise.
Liner Thermal Design	Improved Liner-Cooling Techniques	4.2	1.0	Development of advanced cooling techniques with improved efficiency and reliability.
	High-Temperature Liner Materials	3.6	1.4	Development of high-temperature materials suitable for protective coating or construction of liners.
	Evaluation of Methods for Thermo-Mechanical Liner Analysis	3.3	0.6	Tests to assess the accuracy of existing techniques for predicting thermo-mechanical performance.
Dilution-Zone Design	Advanced Dilution Techniques	1.3	1.1	Development of advanced concepts for optimizing dilution performance.
	Dilution Correlations for Reverse-Flow Annular Combustors	3.0	1.0	Parametric tests to generate data for improved correlations of dilution performance.
	Dilution Correlations for Low-Flow Combustor Geometries	2.9	1.4	Same as above program except focusing on geometries suitable for low-power applications (e.g., slingers).
	Effect of Traverse Quality on Blade Temperature Profiles	2.4	1.7	Tests to measure variation of blade temperatures with exit traverse quality.
	Blade Temperature Measurement Methods	1.0	1.2	Development of procedures and instrumentation for measuring temperatures of static and rotating blades.

(Continued on next page)

TABLE V (Continued) - LIST OF SUGGESTED R&D PROGRAMS

Technology Area	Program Title	Priority Rating		Program Description
		Average Score ¹	Standard Deviation ²	
Modeling	Modeling of Fuel Injection	3.4	1.0	Development of improved computerized submodels.
	Modeling of Primary Zone	3.3	1.3	
	Modeling of Dilution Zone	2.8	1.2	
	Liner Life Prediction	2.6	1.4	
	Liner Thermal Analysis	2.8	1.2	
	Overall Performance Model	1.9	0.9	Integration of submodels into comprehensive computer program for analysis of combustor performance.
Alternative Fuels	Injector Performance with Alternative Fuels	2.7	1.7	Tests to measure the effects of fuel properties on performance of small injectors.
	Feasibility Demonstration of Using Alternative Fuels	2.5	1.8	Tests of fuel blends in representative combustors to identify potential problems.
	Projection of Future Fuels	1.6	1.8	Survey to identify likely fuels and their properties.
	Radiation Characteristics	1.3	1.4	Measurement of radiation properties and development of correlations for liner thermal analysis.
	Chemical Kinetics	1.2	1.5	Measurement of rate constants of relevant chemical reactions.
Other Problem Areas	Carbon Formation and Oxidation	2.6	1.6	Experimental investigation of the processes of carbon production and burnup in small combustors.
	Combustor Needs for Advanced Engines	1.8	1.5	Study to assess the needs of combustors in future advanced engines of unconventional design.
	Smoke Visibility Criterion	1.6	0.9	Study to assess the validity of applying current criteria to small engines.
<p>NOTES:</p> <p>1. Mean value of ratings assigned by members of working group. Scoring basis: 0 - Unnecessary; 1 - Low priority (helpful in advancing significant technology); 2 - Medium priority (important in increasing likelihood of achieving objectives); 3 - High priority (necessary to solve critical problems).</p> <p>2. Conventional definition of standard deviation (σ) of an array of data points:</p> $\sigma = \left[\frac{\sum (x - \bar{x})^2}{N - 1} \right]^{1/2}$ <p>where N is the total number of ratings (x) obtained for each program and \bar{x} is the mean value.</p>				

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modeling of fuel preparation and primary-zone performance. The other aspects of combustor modeling are also important but somewhat lower in priority.

It was generally agreed that the projected requirement for burning alternative fuels represents an important issue. In view of this, it is somewhat surprising to note the relatively low priorities assigned to programs in this area with the exception of the first two listed. A probable explanation is that a large number of studies of alternative fuels are currently being pursued by a variety of investigators. The bulk of the results obtained will most likely be applicable to small combustors. In addition, many of the programs suggested in the other categories include some consideration of alternative-fuel effects. Consequently, the apparent feeling is that a major expenditure of additional effort concentrating specifically on alternative fuels would not be justified.

The final group of suggested programs consists of those which are not conveniently classified under the other categories considered. Two of these deal with the problems of smoke in small combustors. The remaining one relates to anticipating the combustor needs for advanced engines of unconventional design which may be developed in the future.

VI.2 Description of Recommended Programs

In the final session of the forum, the list of programs given in Table V was presented for overall consideration by the participants. An open discussion followed in which the members of the group commented on the relative merits of the individual programs, proposed combining some of the programs which have similar focus, and suggested potential modifications in content and emphasis. At the conclusion of the session, the participants were requested to select and list in order of importance the programs which they felt were the most worthwhile conducting. On the basis of a review and analysis of the responses obtained, we have identified a total of 15 programs which are recommended for support. These are listed in Table VI, and described below, in order of importance.

1. Improved Liner-Cooling Techniques

Objective: to develop practical methods of liner cooling which are considerably more efficient than conventional techniques and acceptable in terms of cost and reliability. Reasonable goals in this regard would be a 50 percent reduction in the amount of cooling air required and a fabrication cost not greater than say 10 percent above current levels.

Content: We anticipate that this objective could be achieved through further development of existing advanced methods such as Lamilloy, transpiration cooling, augmented backside convective cooling and counterflow film cooling. The principal steps involved would be as follows:

TABLE VI. - LIST OF RECOMMENDED R&D PROGRAMS

Rank in Order of Importance	Program Title
1	Improved Liner-Cooling Techniques
2	Parametric Investigation of Combustion Performance
3	Advanced Injector Concepts
4	Advanced Primary-Zone Design Concepts
5	Injector Design Correlations
6	High-Temperature Liner Materials
7	Dilution Correlations for Reverse-Flow Annular Combustors
8	Modeling of Fuel Injection and Primary-Zone Performance
9	Investigation of Slinger Combustors
10	Evaluation of Methods for Thermo-Mechanical Liner Analysis
11	Feasibility Demonstration of Using Alternative Fuels
12	Modeling of Liner Thermal Analysis and Life Prediction
13	Advanced Dilution Techniques
14	Dilution Correlations for Low-Flow Combustor Geometries
15	Modeling of Dilution Zone

- Design and fabrication of a number of representative combustor liners incorporating each of the potential advanced cooling techniques.
- Detailed parametric testing of each liner under combustion conditions with a number of different types of fuel to explore the limits of achievable cooling effectiveness and to obtain a comparative evaluation of performance.
- Analysis and correlation of the data to select the most promising concepts for further evaluation.
- Long-term and thermal-cycling durability tests of the selected concepts to identify structural problem areas.
- Development of design modifications and fabrication techniques which provide acceptable durability and performance with configurations that can be produced at a reasonable cost.

The advanced concepts resulting from the program will be of substantial benefit in helping to insure that liner durability does not present a major stumbling block in achieving the desired increases in engine operating pressure and temperature.

2. Parametric Investigation of Combustion Performance

Objective: to develop useful primary-zone design correlations on the basis of parametric experimental data obtained with configurations representative of small combustors. This will require an extensive experimental investigation in which the major performance criteria are measured for parametric variations in the important design and operating variables.

Content: The experiments should be performed with primary-zone combustors representative of both reverse-flow and axial-flow annular geometries. One or more reference combustors of each type should be tested. These should correspond to idealized configurations designed to eliminate or minimize unwanted geometric effects which are secondary to the purpose of the investigation.

The experiments for each configuration should measure or assess the following quantities:

- Overall combustion efficiency.
- Ignition and weak extinction limits.
- Gaseous emissions and smoke.
- Coke deposition.

- Exit temperature profile.
- Liner wall temperature.

The independent variables whose individual effects are to be determined should include:

- Fuel type, using a selected reference fuel as a baseline.
- Air flow rate.
- Inlet pressure and temperature.
- Fuel/air ratio.
- Liner volume and annulus height.
- Recirculation zone strength and size.
- Amount of film-cooling air.
- Injector spacing.
- Injector type (including simplex, dual-orifice and air blast atomizers) and spray characteristics (SMD and spatial distribution).

Once the test data have been obtained, they should be analyzed to develop the required design correlations. These efforts should be guided by the existing relationships derived for the more-conventional combustor configurations.

In addition to design correlations specific to small combustors, the results of the program outlined here will include a direct comparison of alternative primary-zone concepts, a large data base which can be used in calibrating more sophisticated combustor models, and a better understanding of the relevant primary-zone phenomena.

3. Advanced Injector Concepts

Objective: to identify and evaluate the potential of improved methods of fuel injection which have atomization characteristics that more closely match the unique requirements of small combustors.

Content: The principal goals in developing the advanced injector concepts should be to achieve:

- Good atomization (low SMD and uniform spray dispersion) at low fuel flow rates.
- Low sensitivity of atomization performance to fuel properties.

- High turndown ratio.
- A spray shape (annular rather than conical) which is compatible with achieving uniform circumferential dispersion of fuel.
- A "malleable" spray which can be more easily integrated with the air flow pattern in the primary zone.

Since the airblast atomizer has characteristics which appear to be best suited to satisfying these requirements, the investigation should focus on developing advanced designs based on the airblast principle. However, it should also include other promising techniques such as the spill-return atomizer and the impinging-jet flat-spray nozzle. In addition, it would probably be worthwhile to examine the current state-of-the-art in less conventional techniques such as ultrasonic and electrostatic atomizers to determine their potential for use in solving small-injector problems.

4. Advanced Primary-Zone Design Concepts

Objective: to identify one or more improved concepts for primary zone design and to demonstrate their effectiveness experimentally.

Content: The principal thrust of the program should be to achieve the following:

- A uniform circumferential fuel/air distribution with a minimum number of injectors.
- Heat release rates on the order of 50 percent or more higher than current levels.
- Combustion efficiency of greater than 98 percent at idle and essentially 100 percent at all other conditions.
- Acceptable stability and ignition limits.
- Low soot formation and minimum coking of liner walls.

The key steps in the program would be as follows:

- Selection of reference design conditions representative of the most stringent of those anticipated for future small combustors.
- Identification and evaluation of several potential concepts.
- Design and fabrication of one or more of the most promising.
- Preliminary screening at atmospheric pressure.
- Detailed development testing of the selected concepts.

Although there is no guarantee that all of the goals can be met, the results of the program will be beneficial in advancing the technology required for optimization of primary-zone performance.

5. Injector Design Correlations

Objective: to develop improved correlations for predicting the important spray characteristics of small injectors as functions of operating conditions and design variables.

Content: The principal emphasis should be on investigating the operating regime representative of small combustors. A series of parametric tests should be performed for a number of different advanced injector designs under conditions of pressure and temperature which are as realistic as is practical without combustion. The tests should be devised so as to measure drop size, size distribution, and spatial distribution of fuel/air ratio in the spray for systematic variations of the major geometric and operating parameters. The effects of fuel properties on injector performance should also be examined by conducting tests over a range of properties representative of potential alternative fuels. The experimental data obtained should serve as the basis for developing the required design correlations.

The results of the program will be of significant benefit in improving the accuracy of designing small-injector systems and should provide insights which will be useful in the further development of improved configurations.

6. High-Temperature Liner Materials

Objective: to accelerate the ongoing developments in the technology of high-temperature materials for combustor liners.

Content: The program should address materials for use as protective coatings (e.g., magnesium zirconate) as well as materials suitable for actual construction of the liner (such as, carbon/carbon composites, ceramics, and columbium-based alloys). The key elements of the program would consist of the following:

- Review of the state-of-the-art to identify suitable candidate materials, collect data on critical properties, and assess the extent of the problems which must be overcome.
- Devising low-cost fabrication techniques and approaches to obtaining the desired characteristics (high strength and low oxidation) for the most promising materials.
- Design and fabrication of combustor liners constructed of the selected materials.
- Conducting performance and durability tests to demonstrate feasibility or to identify required modifications.

The results if successful will improve significantly the chances of developing small combustors which can withstand the severe operating conditions anticipated for future engines.

7. Dilution Correlations for Reverse-Flow Annular Combustors

Objective: to develop dilution-zone design correlations which can be applied directly to reverse-flow annular configurations.

Content: An experimental investigation should be conducted for the purpose of obtaining jet penetration and mixing data in geometries which simulate the dilution zone. Tests performed should consist of measuring the variations in velocity and temperature profile with distance along the flowpath for systematic variations in the conventional dilution parameters such as hole size, hole spacing, pressure drop, and air flow rate. Separate series of tests should be conducted with different duct geometries in which the following quantities are varied individually:

- Rate and extent of area convergence.
- Aspect ratio of the turn.
- Location of the dilution holes (upper and lower passage walls).
- Entering profiles of velocity and temperature.
- Amount of upstream swirl.

The data obtained should be analyzed to determine the variation of traverse quality with flow distance as a function of the independent test parameters.

The design correlations resulting from the program should reduce considerably the development time and effort required to achieve a desired value of exit traverse quality for this important type of combustor geometry.

8. Modeling of Fuel Injection and Primary-Zone Performance

Objective: to develop a computerized model which provides an accurate representation of the complex phenomena occurring in the primary zone including the processes of fuel injection and distribution.

Content: A comparative assessment of existing models should be conducted first to determine the approaches which appear to be the most promising. A concentrated effort should then be devoted to achieving the necessary improvements in the selected analytical methods. The problem areas requiring detailed attention were discussed fully in a recent NASA workshop (ref. 24). The key areas include fuel atomization

and vaporization, interaction of the injected fuel with the air flow pattern, chemical kinetics of the relevant reactions, and the effects of turbulence on the primary-zone flowfield.

The principal elements of the study should consist of the following:

- Assessment of the problem areas which need to be addressed.
- Refinement and calibration of the submodels on the basis of available data (presumably including the results obtained in conducting the recommended experimental programs described previously).
- Modification of numerical techniques to improve calculation efficiency and reduce running time.
- Developing procedures which relate the detailed calculation results to overall parameters (such as combustion efficiency, weak extinction limit, etc.) useful to the combustor designer.

The final model should be as generalized as possible so that it can be readily applied to the variety of primary-zone geometries and methods of fuel injection used in small combustors.

The resulting improvements in performance-prediction capabilities should substantially reduce the time, effort, and cost associated with the design and development process.

9. Investigation of Slinger Combustors

Objective: to develop useful design data and correlations for slinger configurations.

Content: An experimental investigation is required which is similar to that described above for conventional geometries (Program No. 2), but somewhat more limited in scope. The program should examine parametrically the effect on combustion performance and exit temperature profile of variations in flow conditions, combustion volume, aerodynamic design and atomization characteristics. In addition, a separate series of tests should be conducted to obtain parametric data on atomization performance as a function of the major slinger design variables including rotational speed and the size and pattern of injection holes in the shaft. The overall data obtained should serve as the basis for developing the necessary empirical correlations of slinger and primary-zone performance.

The program will result in a significant advancement in the design methodology for slinger-based combustors and should enhance the potential utilization of this configuration in future applications.

10. Evaluation of Methods for Thermo-Mechanical Liner Analysis

Objective: to assess the accuracy of existing analytical techniques for predicting thermo-mechanical performance of combustor liners.

Content: The investigation should consist of conducting a set of parametric combustion tests with actual liner configurations aimed at generating the detailed experimental data necessary for comparative evaluation of the available techniques. The principal steps required are as follows:

- Review of current methods for predicting wall temperature and stress distributions, effects of low-cycle fatigue, and ultimate liner life.
- Fabrication of a number of representative liner test configurations including both conventional and advanced cooling techniques and materials.
- Parametric steady-state and cyclic testing of the configurations under actual combustion conditions.
- Comparison of measured and predicted results to determine the validity of the candidate analytical methods.

The program should provide an assessment of the weaknesses in current prediction techniques and a large body of data on which to base further refinement of the most promising methods of thermo-mechanical analysis.

11. Feasibility Demonstration of Using Alternative Fuels

Objective: to identify the likely combustor problems associated with using potential future fuels in small engines.

Content: The program would consist of performance testing a number of representative small combustors using fuel blends selected so as to cover the ranges of properties anticipated in future fuels. The principal tasks would consist of the following:

- Preparation of fuel system, including provisions for blending and preheat.
- Operation of the fuel system on the test stand for an extended duration with no combustion.
- Testing of each combustor over a representative range of operating conditions with a number of different fuel blends. The measurements in these tests would include characteristics such as ignition limits, stability, combustion efficiency, liner temperature, traverse quality, and emissions of NO_x , PAH, and smoke.

- Examination of liners for coke deposition and signs of high-temperature corrosion due to trace metallic elements in the fuels.
- Identification of remedial measures to be evaluated in future investigations.

The main benefit of the program would be in using the results to effectively plan subsequent R&D efforts on future fuels, giving most attention to the critical problem areas which are demonstrated to exist.

12. Modeling of Liner Thermal Analysis and Life Prediction

Objective: to develop improved computerized models for prediction of wall temperature distribution and liner life.

Content: The adequacy of the available techniques for analyzing the various aspects of life prediction including liner thermal analysis should be reviewed. Ideally, this should be based on the results obtained in the recommended experimental investigation described above (Program No. 10). The selected techniques should then be incorporated into a comprehensive computer program. The resulting overall model should then be calibrated on the basis of the available data on liner thermo-mechanical performance. Finally, the model should be verified by applying it to known cases where liner failures have occurred in order to assess the accuracy and utility of the prediction procedure.

13. Advanced Dilution Techniques

Objective: to develop advanced concepts for dilution zone design which are capable of providing acceptable traverse quality with the reduced amounts of dilution air anticipated in future combustors.

Content: The program should consist of devising practical methods which optimize the penetration and mixing of dilution air. Specific goals in this regard would consist of reducing the dilution-zone length required to achieve an acceptable pattern factor with reasonable values of liner pressure drop and low amounts of dilution air. The approaches necessary will most likely involve significant departures from conventional techniques. Possible candidates include for example, injection of the dilution air through chutes or ducts and tailoring of the flow-path to promote rapid mixing. Likely concepts identified in the initial stages of the study should be analyzed to assess their potential. Detailed development testing of the most promising ones should then be conducted using simple ducts which simulate the dilution zone flowpaths of small combustors. The program should focus both on generalized concepts and on specific approaches tailored to the particular features of the different types of small-combustor geometry.

14. Dilution Correlations for Low-Flow Combustor Geometries

Objective: to develop dilution-zone design data and correlations which can be applied to combustor configurations suitable for low-power applications.

Content: This program is similar to the one described above for reverse-flow annular combustors (Program No. 7). The principal exception is that it would focus on those combustor flowpath geometries which are primarily used in applications falling in the lower end of the general-aviation power spectrum. The dilution-zone configurations examined would include those characteristic of single cans with exit scroll, widely-spaced multiple cans with appropriate transition piece, and slingers. Parametric tests of jet penetration and mixing would be conducted to obtain the necessary experimental data on which to base the development of the required dilution correlations for each type of geometry considered.

15. Modeling of Dilution Zone

Objective: to develop a computerized model which provides an accurate representation of the flow field in the dilution zone of small combustors.

Content: The principal steps in obtaining the necessary improvements in dilution-zone modeling are as follows:

- Review of existing aerodynamic submodels of jet penetration and mixing to determine the most promising.
- Incorporation of the selected analytical techniques into a computerized numerical scheme for calculating the detailed velocity and temperature profiles in the dilution zone.
- Calibration and refinement of the computer model on the basis of the available data including the results obtained in the recommended parametric tests of dilution-zone performance.
- Optimization of the numerical techniques to reduce calculation time and improve ease of utilization.

The final version of the overall dilution-zone model should be general enough to be applied to the various geometries encountered in small combustors and should be capable of adequately treating the effects of variations in inlet profile, turbulence level, and degree of incoming swirl.

VI.3 Concluding Remarks

The 15 programs summarized in Table VI form the recommended plan of research and development. The final list of programs and the relative ranking order are based on an evaluation of the prioritized lists submitted by the individual organizations at the conclusion of the forum. A number of different numerical scoring techniques were applied in analyzing the information supplied. Although a fair amount of scatter was apparent in the results obtained, there was general agreement, approaching unanimity, in the choices of the top six programs and their relative ranking order. As would be expected, the degree of uncertainty in the relative priorities increases somewhat for the programs appearing lower down on the list. In general, however, we feel that the results presented here are a fairly accurate reflection of the group consensus regarding the R&D efforts which should be conducted in the 1980-1990 time frame.

The recommended plan includes programs in all of the principal categories of small-combustor design and operation. From an examination of the results, it is fairly obvious that the major concerns of the combustion community are in increasing liner durability, optimizing primary-zone performance, and improving fuel injector technology. The complete group of programs consists of a balanced mix of R&D efforts including the development of advanced concepts, the experimental investigation of fundamental problem areas, and the refinement of analytical engineering tools. In our judgment, the recommended plan of research and development represents an effective broad-based approach to addressing the critical combustor needs and should be pursued aggressively in order to achieve the required advances in small-combustor technology.

VII. CONCLUSIONS

A study of the research and development requirements of small gas-turbine combustors has been conducted. The objective was to formulate an R&D plan for the 1980-1990 time frame which addresses the needs of combustors for turboprop or turboshaft engines of 1490 kw (2000 hp) or less. Our approach involved soliciting the active participation of the major manufacturers and government users of small turbine engines in defining the current and projected combustor needs. This was accomplished by conducting an in-depth survey of these organizations followed by an invitational forum organized for the purpose of reaching a consensus regarding the technical efforts which need to be pursued.

Perhaps not too surprisingly, there was a general consistency among the participating organizations and individuals in their perception of the major problem areas which must be addressed. The principal differences were in the emphasis placed on the individual problems and the corresponding priorities of the research and development needs. The primary conclusions we have reached based on an evaluation of the results obtained in the overall study can be summarized as follows:

- Present-day turboprop and turboshaft engines are similar in overall configuration. The predominant features of most engines include a high-pressure centrifugal compressor stage, an axial turbine which is generally uncooled except in the newer, larger engines, and a reverse-flow annular combustor with fuel injectors of the simplex, dual orifice, or airblast variety. Typical pressure ratios are in the range of 6/1-17/1 and turbine inlet temperatures are generally on the order of 1200-1530°K (1800-2300°F). The average value of SFC is about 1.0×10^{-4} kg/kw-s (0.6 lb/hp-hr).
- The principal current problems in small combustors are associated with achieving acceptable liner cooling, atomization at low flow rates, uniformity of circumferential fuel/air distribution, part-power combustion efficiency, and ignition.
- The major changes in future small engines will be significant increases in operating pressure and temperature to reduce specific fuel consumption, and greater fuel flexibility to cope with the anticipated decrease in availability of conventional fuels. It is expected that pressure ratios will be in the range 12/1-25/1 and turbine inlet temperatures will reach 1400-1700°K (2200-2600°F). The potential also exists for development of new GATE engines of the 190-450 kw (250-600hp) class if government support is provided for the required advances in high-risk technology areas.

- The corresponding future requirements of small combustors will focus on achieving acceptable liner durability under the more severe thermal loading associated with the higher pressure and temperature levels and the use of alternative fuels. The resulting trends will be towards increasingly compact configurations (higher heat release rates) and improvements in liner thermal design in order to maintain cooling-air requirements at acceptable levels. The impacts on other areas of combustor design will be due primarily to the compromises necessary to achieve satisfactory durability.
- The research and development efforts required to meet future needs involve advances in all of the principal aspects of combustor design and operation. The key requirements in this regard include the development of effective liner cooling techniques and high-temperature materials, optimization of primary-zone performance, and improvement of fuel-injection methods. An R&D plan for the 1980-1990 time frame has been developed. This consists of conducting 15 recommended programs involving the development of advanced concepts, experimental investigation of fundamental problem areas, and derivation of improved analytical tools. The recommended plan represents an effective approach for advancing the state-of-the-art in the field of small combustors.

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