NASA Conference Publication 2087

Fundamentals of Gas Turbine Combustion

Melvin Gerstein, *Editor*
University of Southern California

A workshop held at
Lewis Research Center
Cleveland, Ohio
February 6-7, 1979

National Aeronautics and
Space Administration

**Scientific and Technical
Information Office**

1979

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FOREWORD

The Lewis Research Center is the National Aeronautics and Space Administration's principal field installation for research and development required to advance the state of the art and provide technology support in aeronautical propulsion. Basic and applied research in combustion and advanced combustors are a part of this activity. A 2-day workshop was held at the Lewis Research Center to define future research needs relative to gas turbine combustion. The workshop provided the opportunity for combustion experts from government, universities, and industry to meet and discuss a variety of associated problem areas. It is anticipated that the recommendations from this workshop will serve as a guide to NASA in planning future activities in combustion fundamentals.

Participation of NASA personnel was limited to serving in liaison and advisory capacities and giving a brief review of ongoing efforts. This proceedings contains the thoughts and recommendations of the workshop participants as arranged by the Workshop Chairman, Professor Melvin Gerstein of the University of Southern California.

Larry A. Diehl
NASA Lewis Research Center
Workshop Organizer

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PREFACE

This workshop was conceived and sponsored by the NASA Lewis Research Center as a means of bringing together combustion experts from government, universities, and industry to define the major fundamental combustion research problems relevant to aircraft gas turbines.

A total of 26 participants met for 2 days. Included were 13 representatives from universities, 8 from industry, and 5 from the Lewis Research Center, as shown in the table on page vii.

The workshop was opened with welcoming statements by the Chairman (Professor Melvin Gerstein) and the Workshop Organizer (Dr. Larry A. Diehl). Dr. Diehl presented a brief review of the research presently being conducted by the Combustion Fundamentals Section under his direction and a statement of the goals of the fundamental combustion research. Each of the four Chairmen of the working subgroups dealing with Atomization and Vaporization, Combustion Chemistry, Combustion Dynamics, and Combustion Modelling presented a review of his perception of his area of responsibility and the manner in which the subgroup would function. The remainder of the first day was spent in individual meetings of the four subgroups. At the end of the first day, interim reports of the Atomization and Vaporization and Combustion Chemistry subgroups were presented by the respective Chairmen. The Combustion Dynamics and Combustion Modelling reports were presented the morning of the second day by the respective Chairmen of these subgroups. The remainder of the second day was devoted to the preparation of a rough draft report by each subgroup. These reports were combined and modified by each subgroup Chairman prior to being submitted to NASA.

The purpose of the workshop was to prepare a set of fundamental research objectives relevant to aircraft gas turbine combustors. No attempt was made to establish individual priorities among the projects; all the recommendations were considered to be of high priority, having been selected from a large list of research projects. The selection was made on the basis of 2 days of intensive discussion by teams of experts having diverse backgrounds and points of view. These discussions were intensive and frank reviews of various combustion problems, the state of the art, and future needs. If there is any regret, it is that the discussions were not recorded, since they were in-depth discussions by prominent experts and covered many more problems in greater detail than does the final set of recommendations.

It was recognized early that no simple division of topics could account for the complex interaction of all combustion processes in a gas turbine. Therefore, no attempt was made to avoid overlapping discussions and recommendations. At the same time, no effort was made to show all the interactions. It is assumed that these will be evident to the combustion experts who devise a research program based on the individual recommendations.

In conclusion, the Chairman thanks all the participants for their unselfish preparation and the professional manner in which sometimes controversial topics were handled. Special thanks are due the subgroup Chairmen, Professors Arthur H. Lefebvre, Craig T. Bowman, Frank E. Marble, and Arthur M. Mellor, who carried the primary responsibility for developing the final report. We are all grateful to Dr. Larry A. Diehl of the Lewis Research Center for his guidance and to the members of the Lewis staff for their efforts to provide the working group with its needs. The final word of thanks goes to the Lewis management for sponsoring and hosting the workshop and for providing the staff and facilities to support the workshop.

Melvin Gerstein
University of Southern California
Chairman

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FUNDAMENTALS OF GAS TURBINE COMBUSTION

I. INTRODUCTION

The rapid development of the gas turbine for aircraft applications involved a close cooperative effort between government, universities, and industry. NASA/NACA played a leading role in the development of modern high performance aircraft gas turbines not only through its fundamental research, but also in bridging the gap between research and development. The Lewis Research Center activities in propulsion and, specifically, its combustion research, were key factors in the development of the gas turbine and the growth of the industry. This activity became of less urgency during the period of missile and space research. The needs of a new generation of aircraft gas turbine engines places a renewed emphasis on combustion research and on the need for NASA's leadership and participation. Higher speed, larger and longer range aircraft create new needs for improved power-to-weight ratios while the often conflicting demands of energy conservation and pollution control have introduced a new set of problems and restraints.

There has always been a concern about the use of broad specification fuels under emergency conditions - the potential use of alternative fuels derived from shale, tar sands, and coal may introduce fuel and combustion problems for normal operation not just emergency conditions. The emphasis on pollution has varied as the national priorities alternate between energy concerns and environmental concerns. In the long-range, both problems must be faced. There is another, research-oriented, basis for continued research on gas turbine pollutants. Control of pollutants

(CO, NO_x, hydrocarbons) provides a severe test of the understanding and ability to control the combustion process.

The coming era of aircraft gas turbine development brings with it many problems requiring fundamental combustion research. Many of these problems are current, and shorter range efforts are required while others are long-range and fundamental research aimed at these problems must be initiated now. Although combustion research is conducted by many organizations, only NASA has the specific responsibility for commercial aircraft systems. In this sense, NASA has a unique responsibility in this field. There is a need to conduct and support combustion research under controlled conditions without emphasis on specific hardware configurations, but relevant to hardware development needs; to provide long-term, continuous effort on basic combustion research areas; to develop or adapt experimental and theoretical methods for combustor diagnostics available for use by the aircraft industry; and to provide assistance in the development of basic data, correlations, and models relevant to aircraft gas turbine combustors.

The research needs outlined in this report are intended as a guide to NASA in the development of its fundamental combustion program relevant to aircraft gas turbine combustors. Specific priorities have not been attached to each item since the entire list of research areas was selected from a listing of many problems as being of the highest priority.

The listing of research areas is divided into four groups:

1. Atomization and Vaporization
2. Combustion Chemistry
3. Combustion Dynamics
4. Combustion Modelling

These relatively general headings were chosen since it was evident that specific operating problems did not provide a proper base for the discussion of long-range problems. It is evident that most operating problems overlap one or more of these general areas - this overlap is evidenced in several of the discussions and will be reviewed in the summary.

II. ATOMIZATION AND VAPORIZATION

A. Introduction

For current, conventional aircraft combustors, burning Jet A type fuels, the processes of atomization and evaporization are not normally limiting to combustion performance. However, altitude relight capability may be impaired by poor atomization and low evaporation rates, which can also be a significant contributing factor to the emissions of carbon monoxide and unburned hydrocarbons at idle conditions and to the production of soot and nitric oxides at high power conditions.

It is anticipated that some of the advanced combustor concepts that are now being developed for ultra-low emissions applications, such as, for example, premixed/prevaporized systems and catalytic combustors, will pose formidable problems in regard to the attainment of satisfactory levels of spray quality and fuel evaporation rates. For all types of combustor, these problems will be aggravated by the trend towards fuels of high aromatic content and will be especially severe for the so-called "alternative fuels" produced from oil shales, tar sands, and, perhaps, even coal.

For all these reasons, it is considered timely to examine current knowledge of the processes of fuel atomization and evaporation in order to identify "areas of ignorance" which, if neglected, could prove limiting to combustor design and performance in the future.

B. Research Areas

1. Drop-Size Measurement

Since fuel drop size can have a pronounced affect on many aspects of combustion performance, and bearing in mind that its influence will assume much greater significance in the future, it is clearly important to be able to measure drop size accurately. The various approaches to drop-size measurement tend to fall into three main categories of direct, photographic, and light-scattering or light diffraction methods.

Direct methods include the use of a magnesium oxide-coated slide on which the drops impinge and are subsequently counted and measured. A defect of this method is that it fails to collect the smallest drops. Other direct methods include the "wax droplet" technique, which was developed by Joyce some thirty years ago, and the more recent "nitrogen-freezing" technique in which the fuel drops are collected in an isokinetic probe and rapidly frozen by nitrogen gas. The frozen drops are then photographed, and the photographic print is placed in a "Quantimet" or some other form of drop-size analyzer in order to obtain a "print-out" of the drop sizes or drop-size distributions. The drawback to these direct methods is that correction factors must be applied which are sometimes fairly substantial, and they are all tedious and time-consuming.

Many photographic techniques have been used with varying degrees of success to measure the drop sizes in a spray. Of these, the one which has had by far the greatest application to gas turbine nozzles is the Parker-Hannifin High Speed Analyzer. This instrument has been used to study in detail the spray characteristics of large numbers of pressure/swirl and airblast atomizers. It uses a 0.5 microsecond flash to photograph the droplets contained within a small frame of 1.5 x 2.0 mm and approximately 1 mm in depth. The resolution of the system is within 4 microns. The rate of photography is 15 frames per second. A complete test takes about 20 minutes and will encompass more than 14,000 drops. Most of our present knowledge on the drop-size distribution of gas turbine fuel nozzles was gained from this device.

Within the last few years, the Malvern instrument has appeared on the market and is finding widespread application. It is based on light diffraction principles and assumes a Rosin-Rammler drop-size distribution. Essentially, it provides the two main constants in the Rosin-Rammler expression which together define the spray. Its advantage is that it offers a semi-standardized procedure, and also, it embodies some built-in checks for accuracy.

A light-scattering technique has been used successfully at Cranfield for more than a decade to study the spray characteristics of pressure/swirl and airblast atomizers. It is quick and has good repeatability, but it provides only a measure of SMD (Sauter Mean Diameter) and provides no information on the drop-size distribution in the spray.

The growing in fuel atomization has led in recent years to the development of several new laser scattering and intensity ratioing techniques. The latter offers considerable promise for the accurate measurement of drop sizes in the very small size range, say from 0.3 to 3 microns, while laser scattering should prove useful in the range of 10 microns. So far, these new techniques have been tested only under "cold" conditions, but they are now being applied to the more hostile combustion situation.

The group considers that the amount of effort now being expended on drop-size measurement is satisfactory. A major deficiency, however, is that at this point in time there is no "absolute" method available against which to calibrate or check the accuracy of any other. The various proposed solutions to this problem include the use of "sprays" composed of solid particles of known size. The Malvern instrument is considered accurate in the range from 20 to 130 microns SMD, while the Parker analyzer is accurate in the range from 80 to 200 microns SMD. The term "accurate" is in this context is intended to imply a repeatability of $\pm$ 6%. As stated earlier, no absolute standard of measurement exists. However, the group feels that drop sizes can be measured with sufficient accuracy for most practical purposes within the range of SMD from 20 to 200 microns. Some of the new techniques now being developed will improve on this accuracy and will also extend the range of measurement down to sub-micron sizes.

2. Mechanism of Drop Formation

Although our current lack of knowledge on the detailed mechanism of drop formation (i.e., whether it occurs as a result of wave instability or from ligaments) is not limiting to nozzle design, it is felt that some photographic studies in this area could prove profitable when the atomization problem assumes much larger proportions, e.g., for alternative fuels.

3. Spray Characteristics

For both pressure/swirl and airblast atomizers, the fuel nozzle designer can now provide within close limits, any required radial fuel "patternation". However, a major unknown is the extent to which these characteristics are modified when the nozzle is installed in the liner.

Research is needed to study the influence of primary-zone aerodynamics on spray characteristics under the following conditions: a) nozzle only; b) nozzle in combustor (cold); and c) nozzle in combustor (burning).

For both pressure/swirl and airblast atomizers, much is known about the effects of fuel properties - viscosity, density and surface tension, and air properties on mean drop size. However, more work is needed on the effects of all properties (fuel and air) at the conditions of high pressure (30 atms) and corresponding high temperatures encountered in modern turbojet engines. Such measurements are especially important for the alternative fuels.

For the prefilming type of airblast atomizer, the prefilming process should be studied in more detail. In particular, measurements of fuel film thickness at the atomizing edge should be carried out: a) to determine the relationship between fuel film thickness and mean drop size; and b) to study the circumferential variation of film thickness, if any, and its relationship to the number, size, and shape of the fuel injection ports.

4. Alternative Fuel Problems

The group is very concerned about alternative fuels. In general, they have relatively high viscosity and low volatility which have an adverse effect on, respectively, atomization quality and fuel evaporation rates. The effect of viscosity is much less for the airblast atomizer than for the pressure/swirl atomizer. To obtain rates of evaporation that are comparable to current fuels, much better atomization will be needed. The problem is aggravated by the fact that the thermal stability of the alternative fuels (and also the fuels now being contemplated of high aromatic content) is so low that the heat insulation devices that must be incorporated into the fuel nozzle to reduce heat soakage could reduce the aerodynamic efficiency of the airblast nozzle and thereby impair atomization quality.

It is possible that the problems of atomization posed by the alternative fuels could become so severe that serious consideration may have to be given to "air assist" atomizers which require a separate supply of high pressure air. If the problems of atomization of alternative fuels are mainly confined to ignition, then perhaps a torch igniter supplied with gaseous fuel could prove a more attractive proposition.

In any case, the physical and chemical properties of the alternative fuels should be investigated in detail in order to determine the severity of the atomization and evaporation problems.

5. Vaporization

It is clear that much needs to be learned about the evaporation process. As we develop the alternative fuels, vaporization can be expected to become a rate-controlling factor since the volatility will be lower. In order to predict the performance and emissions of combustors, it will be necessary to understand the details of vaporization better than at present. The gaseous mixture-ratio distribution will depend critically upon droplet trajectories and vaporization rates. This ratio has a critical affect upon burning rates, soot formation rates, and other pollutant formation rates.

In order to understand vaporization processes and to develop a predictive capability, various fundamental studies are required. Classical droplet vaporization theory deals with a quasi-steady, spherically-symmetric, single-component droplet which is isolated and vaporizes smoothly to completion. In practice, we are often interested in transient, convective, multicomponent droplet vaporization where there is strong interaction between droplets and where secondary atomization (of various types) may occur. In recent years, some modest experimental and theoretical studies of these problems have begun. Accomplishments have been sufficient to demonstrate that such efforts are worthwhile. However, more research is needed in order to reach the overall engineering goal of a predictive capability.

The transient aspect of droplet vaporization must be carefully studied. Cold droplets are injected into hot environments and experience heating. With the heavier, alternative fuels, boiling points of the less volatile components will be increased (especially as technology tends towards higher pressure operation). The droplets do not stabilize at a wet-bulb temperature, but rather are continually experiencing an increase in temperature.

The larger droplets will travel through the hot, oxidizing gas in a combustor with a significant Reynolds number based upon relative velocity. The flow field around the droplet is therefore quite complex; also, internal droplet circulation can occur. Convective heat and mass transfer processes play an important role in determining vaporization rates, requiring detailed study.

The droplet will have many components with a range of volatility. Therefore, a vaporization rate should be determined for each component with liquid-phase mass diffusion having its importance in bringing fresh volatiles to the liquid surface. The more volatile components would tend to vaporize earlier than the less volatile components. Since the droplet is moving through the gas while it vaporizes, the composition of the fuel vapor will vary throughout the combustor. This could significantly affect flame stabilization and soot formation.

There will be domains within the combustor where the distance between droplets is sufficiently small so that vaporization rates are affected by the proximity of other droplets. Furthermore, if moving droplets are dense, the entrainment of gas will be quite significant. A diffusion flame may surround a large group of droplets rather than many individual flames surrounding droplets. Experimental and analytical studies of these phenomena would be timely.

Various mechanisms of secondary atomization could occur: impingement on solid surfaces, rapid acceleration, and microexplosions (for either multicomponent or emulsified fuels). It may be desirable, in some cases, to design for secondary atomization in order to enhance vaporization. Again, further research is required in order to enhance vaporization. Again, further research is required in order to develop a predictive capability and to evaluate any advantages of secondary atomization.

The above-mentioned tasks are formidable and require some time. In the meantime, some gross data could be obtained from measurements on the rate of evaporation of sprays injected into flowing air streams at: a) relatively low air temperature for premixed/prevaporized and catalytic combustor applications; and b) high temperature conditions, preferable burning.

There is a need to measure vapor pressure as a function of temperature over the entire distillation curve. This is needed for all alternative fuels and should prove valuable in the study of cenosphere formation.

C. Summary of Recommendations

1. Developments in drop-size measuring techniques are proceeding satisfactorily, and no major additional efforts are required. It would prove most useful if some absolute standard could be established against which to compare the accuracy of other techniques.

2. Drop-size measurements and initial spatial distribution of drop sizes are needed for all the main types of atomizer, especially at conditions of high pressure and temperature. This is especially true for the high aromatic and alternative fuels.

3. For prefilming airblast atomizers the influence of prefilmer shape should be investigated, and more measurements of film thickness obtained to establish the relationships between film thickness, fuel drop size, and atomizer geometry.

4. In recognition of the growing integration of fuel injector and primary zone aerodynamics, it is recommended that the influence of combustor aerodynamics on fuel spray characteristics should be examined experimentally under both cold and burning conditions.

5. Fundamental studies of droplet evaporation should be conducted with transient, convective, multicomponent droplets. Vaporization of droplet arrays or sprays and secondary atomization must also be examined in detail.

6. Measurements of spray evaporation rates of sprays injected into flowing air streams should be conducted for both cold air and hot air streams.

7. The physical and chemical properties of alternative fuels should be established in detail in order to allow a proper assessment of the magnitude of the anticipated problems of atomization and evaporation.

8. Although atomization and evaporation are not normally limiting to the performance of conventional aircraft combustors burning current aviation fuels, they are expected to pose formidable problems with alternative fuels (atomization, evaporation, and thermal stability) and also for premixed/prevaporized combustors which rely on very fine atomization (≃ 20 microns SMD) for their successful operation.

III. COMBUSTION CHEMISTRY

A. Introduction

Many of the combustion-related problems of gas turbines involve the coupling of chemistry with physical phenomena such as fuel vaporization and turbulent transport. This section of the report does not explicitly consider this coupling but rather focuses on important fundamental problems in homogeneous and heterogeneous chemical reactions as related to gas turbine combustion. The Working Group identified four areas where additional research is required, and some specific research objectives in these areas are recommended. In addition, we believe that it is necessary to carry out a companion research program aimed at developing and extending the data base for the reaction kinetics of elementary reactions important in combustion and pollutant formation chemistry.

B. Research Areas

1. Thermal Stability of Liquid Hydrocarbon Fuels

Lean, prevaporized, premixed (LPP) combustors require prevaporization and fuel staging. As a result, liquid phase reactions occurring external to the combustor may have an influence on combustor performance. Surface fouling appears to be the greatest potential problem. This is particularly true for staged combustors at low power operation. Secondary reactions between oxidation products (from dissolved oxygen) in the presence of metal surfaces can lead to surface deposits and flow maldistributions. The nature of these reactions and the influence of the surface and the effects of impurities need to be studied. Prevaporization schemes also suggest areas for future research. Several schemes have been suggested for fuel prevaporization such as surface vaporization, flash vaporization, partial combustion, spray injection into combustion products, or combinations of the above. All involve O_2/fuel reactions under very rich conditions. Liquid or vapor phase reactions may be important depending upon the application. Similar comments apply to staged fuel systems where one stage is inoperative and residual fuel vaporizes within the manifold.

The following research areas are suggested:

a. Chemical Effects in Fuel Heating and Vaporization

Study the influence of heat transfer rate, heat transfer mode, pressure, and impurities on liquid and vapor phase reactions for pure fuels and fuel blends vaporizing into inert and oxidizing atmospheres. Liquid phase and very rich vapor phase reactions are of primary interest. The results of this work would be relevant to the design of vaporizers and staged fuel systems and in the study of the effects of liquid phase reactions on soot production.

b. Role of Surface in Liquid Phase Reactions

Study the influence of metal surfaces on the rate of oxidative decomposition of fuels and the nature of liquid and solid product distributions. This project should be preceded by a good literature search in order to define plausible mechanisms leading to surface fouling.

Some work on thermal stability of fuels currently is in progress at NASA-Lewis. We recommend that this program be expanded to permit the detailed study of chemical reactions in the liquid phase (see 1a) and to permit correlation of these observations with surface deposition (see 1b) and soot production (see 4 following).

2. Formation and Destruction of Pollutants

Pollutant emissions will continue to be a significant combustion-related problem in gas turbines, particularly with increased utilization of alternative hydrocarbon fuels which will likely have increased C/H ratios and may have significant levels of organic nitrogen. It seems likely that sulfur in the fuel will have to be removed to reduce turbine corrosion due to sulfadation. Thermal stability requirements may dictate reduction (or complete removal) of organic nitrogen from the fuel, and existing procedures for nitrogen removal. Since it appears that sulfur will not be present in future gas turbine fuels, we have not recommended investigation of sulfur chemistry in combustion. Furthermore, there is an ongoing EPA-funded effort to study sulfur oxidation and the interaction between sulfur chemistry and the nitrogen oxide formation process in flames.

Organic nitrogen compounds present in the fuel can result in increased nitrogen oxide emissions from gas turbine combustors and also can result in production of HCN and NH_3 in fuel-rich regions. Although the fuel-nitrogen conversion process in flames is an active research area, a number of important questions remain unanswered. The following research programs are recommended:

a. HCN Reaction Kinetics

High temperature rate constants are needed for HCN dissociation and radical attack upon HCN. HCN is an observed intermediate in NO formation from fuel-bound nitrogen and further characterization is required. Such information should be available from careful shock tube studies which could be supplemented by more specific high temperature flow system work.

b. Pyrolysis of Organic Nitrogen Compounds

Phenomenological studies are required to check the common assumption that fuel-bound nitrogen rapidly pyrolyzes to HCN. Here particular emphasis should be placed upon product formation studies. Reasonable candidates for study here include pyridine, pyrrole, and an aromatic amine. Some type of mass spectroscopic diagnostic could be most useful here.

c. Hydrocarbon - NO Reactions

There is evidence to suggest that hydrocarbon fragments are important in the NO reaction mechanism, and may well be of consequence in both production and decay of NO. Additional kinetic studies of the rate of attack of these fragments upon both N_2 and NO would help clarify this area.

d. Reaction Between NH_i-NO

Another area involved the kinetics of the reactions of both NH_2 and NH with NO. Such reactions could be important in the combustion zone where NH_3 may be present. It is also important to understand these reactions to characterize the process of NO reduction by addition of NH_3 to the exhaust gases.

e. Fuel Nitrogen Conversion Correlations

Correlations have been developed which relate NO yields to fuel nitrogen levels in a variety of flames. Extension of these studies using diagnostics to measure radical concentrations could lead to identification of the chemical nature of the scaling factor in these correlations. In addition to direct mechanistic implications, this information should provide a firmer basis for extending these correlations to other conditions.

An increase in C/H ratio can result in increased smoke production. Two research areas in the area of soot formation in combustion are recommended.

f. Role of Liquid-Phase Reactions on Soot Production

Study of influence of liquid-phase reactions on soot production in liquid fuel diffusion flames for a range of pure and "thermally-cracked" fuels could be the byproducts of the reactor used in the study of the chemical effects of fuel heating and vaporization (see B1).

g. Effects of Additives on Soot Agglomeration

There is some experimental evidence to suggest that various smoke reducing additives alter soot particle size distribution without significantly changing soot loadings. The mechanism for this process is poorly understood and further research in this area is required.

3. Combustion of Hydrocarbon Fuels

NASA-Lewis has in the past contributed to the area of fundamental combustion chemistry research through shock tube studies of various high temperature elementary reactions which comprise the hydrogen-carbon monoxide and methane oxidation mechanisms. Further reaction studies of this kind would be worthwhile particularly for the elementary reactions of hydroxyl radicals, oxygen atoms, and hydrogen atoms with formaldehyde, formyl radicals, and aromatic molecules.

There are several areas of engineering-oriented studies to which we believe NASA-Lewis could readily contribute, and which are important to improving our modelling of gas turbine combustion.

a. Simplistic Hydrocarbon and Combustion Models

In developing/verifying simplistic combustion chemistry models suitable for use in multi-dimensional, time dependent modelling of combustion flow fields, there is little doubt that the most favorable position from which to begin is from the point of having assembled a nearly complete elementary kinetic mechanism. For some simpler fuel species (H_2, CO, CH_4, CH_3OH, C_2H, C_2H_4, C_2H_6) this is obviously possible for a limited range of environmental variables (pressure, equivalence ratio, temperature). For more complex and more representative fuels, higher alkanes, aromatics, blends, this approach to the construction of simplistic models probably is not presently possible, and will require further elucidation of the mechanistic structure and required elementary rate data. However, the extension of the detailed approach described above to encompass the required range of combustion conditions in gas turbines ($P = 1 - 30$ atm, $T = 700 - 2200K$, $\phi = 0.25 - 3.0$) as well as the development of simplistic models directly from the experimental data (quasi-global, semi-global, lumped parameter approaches) will require a considerable extension of the currently available data base on high temperature ($T > 1400$), high pressure ($P > 1$ atm) hydrocarbon oxidation reaction kinetics. Characteristic parameter definitions (e.g., ignition delay, time) generally are too limited information and must be supplemented by "real time" profile data for both stable and unstable species. Species of most importance include carbon monoxide, carbon dioxide, water vapor, and some measure of the hydrocarbon concentration. It would be desirable to have a breakdown of the hydrocarbons by structure into aliphatic, olefinic, and aromatic content. Additional radical species profile data (OH, O) would be useful in developing more sophisticated mechanisms which could be adequately coupled with NO_x and soot formation mechanisms.

Current understanding of hydrocarbon oxidation suggests key compounds to study are: simple paraffins; ethane, propane, butane, and hexane, at least one cycloparaffin; (e.g. cyclohexane), olefinic structures (at least ethene and propene); simple aromatic structures (benzene, toluene, and xylenes).

Available candidate experimental techniques for these studies are the shock tube and basic pyrolysis/oxidation approaches. Key diagnostic techniques include time resolved laser diagnostic techniques (resonance absorption, fluorescence, etc.) as we-l as more common emission/absorption techniques. Admittedly, the experiments would be less precise than one would desire in developing elementary rate data, but neither detailed nor simplistic models can be properly constructed and validated without such data.

b. Ignition and Extinction of Limit Mixtures

Ignition and extinction of fuel-lean and fuel-rich limit mixtures of hydrocarbon fuels and air are important from the standpoint of flame stabilization and quenching of hydrocarbons. The effects of water vapor, pressure, and added promotors on the "steady-state" (laminar) ignition should be investigated with the objective of determining changes in oxidation mechanisms which occur near flammability limits. These studies will assist in identification of species and rate-controlling reactions which can be the subject of further study under well-controlled conditions (see 4). In addition, results from these studies will serve to test the validity of the hydrocarbon combustion models (see 3a).

A companion program to investigate the "steady-state" extinction behavior of near-limit mixtures also is recommended.

Eventually, it is worthwhile to study the effects of non-steady state conditions (e.g. turbulence) on the ignition and extinction process.

4. Fundamental Chemical Kinetics Research in Support of Combustion Chemistry

Since it is a formidable task to measure all rate constants required for adequate combustion modelling, it is necessary to develop and refine the general framework which allows the extrapolation and interpolation of the currently available data base. Specific experiments should be designed to confirm or modify our understanding of the framework as often as to measure the rates of specific processes identified as important in a specific instance.

Experiments should be designed to test our understanding of products, pressure, and temperature dependences of rate processes as well as the possible effect of the presence of other species. Research programs which are needed include:

a. Radical-Radical Reactions

Disproportionation reactions suffer from a dearth of data and the combustion reactions require an understanding of the energy transfer limitations that lead to pressure as well as temperature dependence. Radical interactions of this type are important in determining the overall rate of the combustion processes, since these reactions are radical removal steps. Specific radicals (of importance in real combustion systems) which would make a good starting set are: HO_2, $C_6H_5CH_2$ (benzyl) and C_3H_5 (aklyl).

b. Temperature Dependence of Biomolecular Processes Over a Large Temperature Range

This is necessary to test the main framework notions of transition-state theory. Data exist for many elementary reactions over the range

$300 \leq T \leq 700$. In order to extrapolate these data to higher temperatures, transition state theory usually is applied. This extrapolation technique has been successfully developed for several metathesis reactions, but should be extended to other types of processes. One example would be $O + C_2H_4$ which is well studied at modest temperatures. Other examples could be: $OH + C_2H_4$, and $OH + C_3H_6$ which have also been studied at room temperature. In the latter case, the relative importance of the addition and abstraction paths would be an important piece of information.

c. Thermochemical Data for Reactive Species

These data are required as a baseline for most mechanical studies. Specific species to be studied would depend on the sensitivity of important rate constants for these parameters. CN radical heat of formation is uncertain to approximately 4 k cal $mole^{-1}$ and should be determined with better accuracy. In addition, as alternative (heavily aromatic) fuels become important, it will be necessary to determine prototype bond energies in these systems. Examples include the C-H bond in napthalene (for comparison with benzene) and the $R-CH_2-H$ bond where R is a polynuclear aromatic ring system such as naphthyl or anthracyl.

d. General Reaction Kinetics Studies

In addition, there will always be processes which are important in specific situations and which must be independently measured. This remains true for several reasons:

First, the data base may not be available for estimating the rates of these processes. Some examples include reactions of the type $RH + O_2$, where RH should be extended to include prototype fuel molecules such as ethane, propane, isobutane, ethene, propene, benzene, toluene, and methyl naphthalene.

Second, the sensitivity of a given process to the rate constant is so great that it must be known very accurately. For example, this may be true of many of the NO forming reactions.

Third, even though the rate constant for interaction of reactive species is known, the products may not be, especially when several pathways are possible. Reactions of some importance in this category will include O, OH, HO_2 reacting with a hydrocarbon. Starting points could be reactions with substituted aromatics such as OH + toluene.

D. Summary of Recommendations

1. Study the influence of heat transfer rate and mode, pressure, and impurities on liquid and vapor phase reactions for pure fuels and fuel blends vaporizing into inert and oxidizing atmospheres.

2. Study the influence of metal surfaces on the rate of oxidative decomposition of fuels and the nature of liquid and solid product distributions.

3. Determine high temperature rate constants for HCN formation from fuel-bound nitrogen compounds, HCN dissociation, and HCN-radical reactions.

4. Establish the role of hydrocarbon fragments and soot (smoke) on NO production and decay.

5. Determine the kinetics of reactions of NH_2 and NH with NO.

6. Extend existing correlations between fuel-bound nitrogen and NO production.

7. Study the influence of liquid-phase reactions on carbon formation.

8. Study the effects of additives on soot agglomeration.

9. Extend the data base on high temperature (T > 1400), high pressure (P > 1 atm) oxidation of high molecular weight hydrocarbons with emphasis on the development of reliable global, quasi-global, and lumped parameter relations.

10. Investigate the effects of water vapor, pressure, and parameters on the ignition and extinction limits of hydrocarbon-air mixtures.

11. To support the above research areas, experimental work is needed to a) evaluate the coefficients of specific radical-radical interactions; b) determine the temperature dependence of biomolecular processes over a large temperature range (non-Arrhenius behavior); and c) to extend thermochemical data base important radical and molecular species.

IV. COMBUSTION DYNAMICS

A. Introduction

Combustion dynamics is interpreted here at that large class of problems in which gas dynamics and chemical kinetics interact in a manner essential to the combustion, or in which the gas dynamic phenomena are dominant. As a consequence, such topics as flame holding technology, combustion instability, emission production, and turbulent combustion are included. In the following paragraphs certain of these topics, and by no means a uniform distribution, have been recommended consideration in a basic combustion research program. There is no attempt to suggest priorities within this selection. In addition, it has been suggested that serious consideration be given to the development of experimental diagnostic techniques for use in engine development as well as for laboratory research use. Finally, a series of combustor related problems, pertaining to the effects of compressor discharge velocity profiles, combustor lines cooling for lean burners, combustor materials, etc. Although these latter topics are not part of a fundamental combustion program, they constitute limitations which are equally severe as the questions of detailed combustion.

B. Research Areas

1. Combustion in Turbulent Mixing Regions

The long-standing problem of turbulent combustion in premixed and diffusion flames has found new life from the recent advances in studies of isothermal inhomogeneous turbulence, in particular, the recognition of large-scale structures. Promising experimental techniques and stimulating effects in turbulence modelling place turbulent combustion high on the list of fundamental research topics.

One problem of fundamental and practical importance is the turbulent mixing and ignition in the mixing layer between streams of premixed fuel/air and of hot combustion products. This configuration contains the essential points of the flame stabilization mechanism for bluff bodies and separated flows. If the hot gas stream is of finite extent in the direction of flow, the mechanics of the blow-off process is reproduced.

Some current views of turbulent flames, both diffusion and premixed, consider a collection of laminar flame elements that are being stretched in their own plane. In this picture, intense turbulent straining causes strain-induced extinction, particularly in vitiated systems. This structure and the attendant extinction processes, which are at present based more upon conjecture than observations, are of vital significance both in the understanding of the structure of turbulent flames and in the production of NO, CO, and unburned hydrocarbon trace species.

The general problem of flame spreading in turbulent flow, such as the propagation of a flame stabilized on a bluff object is again important because of its practical as well as fundamental importance. Detailed studies of these flame spreading phenomena have been somewhat sporadic and with less complete detail than would be desirable with current diagnostic techniques. Because of anticipated conditions of burner operation, it is important that such experiments be carried out, in good experimental detail, for a wide range of pressures, inlet temperatures, fuel types, and air vitiation. Flame spreading in a lean primary burner is an example of one part of the range that is inadequately explored.

Turbulent flame spreading in unusual circumstances also merits attention. The approach conditions to a stabilized flame as well as the wall boundary conditions affect the gas dynamic field and the local spreading mechanism. Problems that are peculiar to staged combustion, in parallel or in series, appear both important and little understood.

In the same general line are efforts to enhance flame spreading by introducing secondary gas motions on concentrated vorticity ahead of the flame.

2. Spray Evaporation, Mixing, and Combustion

Conventional designs for primary engine combustors have introduced fuel into combustion chambers by the technique of injecting liquid fuel sprays into regions of the combustor where strong recirculation of burning products of combustion act to enhance droplet evaporation and to stabilize the combustion process. In current engine development, work on lean premixed, prevaporized combustion, fuel is injected directly into the air stream upstream of the combustion chamber and burning takes place in a premixed-vaporized mixture. Mixing and vaporization must be carried out in very small volumes and in times of the order of 2 ms or less. The speed of the gas passing the injector is of the order of 20 to 100 m/sec.

For both these systems, the gas flow in the neighborhood of its injector strongly affects the injection processes. Although the nature of those effects can now be predicted in only a qualitative manner at best, many highly efficient conventional primary burners have been designed and are currently in use. However, the development efforts required to perfect these designs were long and costly, and were based on the wisdom acquired over a considerable period. This accumulation of wisdom is not available when we consider the design of injector systems and is largely lacking when we attempt to understand the effects of injection system on the production of small amounts of pollutants.

Hence, we suggest that studies be undertaken to determine the characteristics of the sprays produced by injection systems operating in the environment actually encountered in engines. This study should examine fuel distribution patterns, the droplet size distribution, and evaporation rate distribution as a function of the properties of the flow field imposed on the injector. The magnitudes of the gas speed, temperature, and pressure should be varied in addition to the usual fuel-spray parameters and the geometry of the flow field near the injector. As part of this study, the properties of the injection system operating in a quiescent atmosphere should be studied to supply a datum from which changes due to the various aerodynamic parameters can be related.

This study should be extended to investigate the effects on the injection system, the spray pattern it produces, and the subsequent combustion of large and small amplitude pressure disturbances. These disturbances should be modelled as if they arose in either the compressor exit or turbine inlet ducts and the purpose of the measurements is to determine the transient response of the complete burner system. Thus, we want to determine the transfer function for the system.

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suggest that periodic oscillations of incoming air jets can provide much needed cooling for combustor components. Thus, if the presence of self-excited oscillations in the combustor can be tolerated, their beneficial aspects may lead to improved engine performance.

4. Non-Steady Problems Induced by Changes of Engine Operating Point

In lean, prevaporized, premixed (LPP) combustor, the operating point is normally close to the lean extinction limit, fast and large amplitude change of operating conditions or disturbances may induce a flame-out, flashback, or autoignition which are highly undesirable. Limited experience with laboratory flames indicates that near-limit flames are sensitive to disturbances. A thorough investigation, both experimental and theoretical, should be conducted to study these dynamically-induced phenomena.

5. Catlaytic Combustion

Catalytic combustor is rather unique in its capability of burning very lean mixture in a clean, efficient and stable manner. The better pattern factor from the catalytic combustor gas outflux also can lead to a higher engine performance due to the possibility of a less conservative turbine design. In addition, other potential troubles in ordinary LPP system such as flame-out, relight, and instability are likely to be less severe with the catalytic combustors. The catalytic combustor is a new combustor, drastically different from the conventional ones. Therefore, other areas such as catalyst life, poisoning, and thermal shock resistance have to be investigated. The potential payoff of the catalytic combustor can be great. It is recommended that a moderate size program on catalytic combustion fundamentals be supported.

6. Diagnostic Techniques

Complete understanding of combustion phenomena are currently limited by many factors. One of these limitations is the current capability in measurements. Although considerable effort has been and apparently is still being applied in this area, continued effort is strongly recommended. One of the problems is that advancements in diagnostic techniques are often tied to or are funded as part of other programs that have other goals as the major objective. That is, the major activity is to collect some set of data. The investigator then finds himself having to expend a disappropriate portion of the available funding to develop and check out the measurement tool. This can lead to skimping or doing a half-way job in one of the two areas - measurements development or data collection. Therefore, it is recommended that wherever possible, measurements development should be supported separately from the development activity in which the techniques are to be used.

It is important to consider separately the problems of developing highly sensitive and accurate laboratory instrumentation and the more rugged and possibly less accurate instrumentation that is capable of use for making engine measurements. Both of these areas need considerable attention.

Some specific areas of measurement that deserve priority are:

a. Compressor Outlet Turbulence Measurements

Several recent efforts to make these measurements were limited by probe failures at high engine power conditions. Measurements at higher power conditions are required. Also, measurements at additional stations along the diffuser and into the combustor passage areas is required to determine the decay in intensity. This information would be useful in designing and developing premixing systems.

b. Combustor Outlet Temperature and Gas Composition Fluctuations

The temperature fluctuations can probably be done in a much shorter time basis than measurements of the dynamic gas compositions. The temperature measurement would be of interest to the turbine designer for life studies and for studies of turbine nozzle performance as well as for relating back to the combustion process for improved understanding. Also, the temperature fluctuations may be useful in efforts to understand and reduce combustion originated noise.

c. Time Resolved Temperature, Velocity, and Composition in Turbulent Flames

Dynamic measurement techniques of the gas temperature, velocity, and composition should eventually be extended to consider turbulent flames (combustor primary zone) through a larger range basis than for conditions at the combustor exit. This information would greatly improve the understanding of the combustion process and would be used for improving upon or verifying combustion models.

d. Spray Droplet Measurement

One area that has recently been given more attention but deserves considerable more effort is in measuring spray droplet sizes and distribution for actual fuel injectors. At present, most work is done at one atmosphere pressure conditions and cold flow conditions (where swirlers and fuel injectors are tested together). Measurements development should be continued to extend routine testing to actual engine operating pressures with heated air. This capability is required for improvement of existing fuel injector/swirl cup systems and for development of lean, premixed systems.

7. Flame Stabilization in Premixed Systems

Although many fluid dynamic aspects of flame stabilization by bluff bodies in premixed fuel-air streams are well understood, the dependence of the process on chemical parameters and a few fluid dynamic parameters have not been thoroughly investigated. We suggest that an extensive set of measurements be carried out to clarify this dependence. In particular, experiments should be carried out in which pressure, temperature, fuel, and oxidizer characteristics, inlet velocity profile, and turbulence levels are varied through wide ranges. The burner inlet and outlet conditions should be controlled and measured carefully to allow unambiguous interpretation of the data.

We suggest that the range of parameters include:

a) $0.5 \lesssim$ Pressure $\simeq$ 40 atm

b) $300^{o}k \simeq$ Temperature $\simeq 1400^{o}k$

c) New and conventional hydrocarbon fuels and hydrogen

d) $0.10 \simeq$ Partial pressure of oxygen in air $\simeq 0.21$

e) The turbulence levels and profile nonuniformities be used which range from typical turbine outlet conditions to low turbulence level streams with uniform velocity and temperature profiles.

A systematic study should be made of: blow-off limits on the lean fuel-air ratio side, recirculation zone geometry (e.g., zone length and width near the stability limits), the composition and temperature of recirculation gas and the velocity in the turbulent gas near the recirculation zone boundary. Mean velocity and temperatures in the mixing zones should be measured in representative examples.

The data should be analyzed according to several existing models of flame stabilization and used to determine the most useful modelling approach.

8. Combustor-Related Problems

Diffuser performance and problems of separation at the inlet to combustor systems have either been neglected or merely tolerated for the most part in the past. The preliminary design studies made during the early phases of the Stratosphere Cruise Emissions Reduction Program have emphasized the importance of a better defined if not clean flow path into the premixed prevaporizing passages required for these new combustor concepts. The systematic development of a very lean, premixed, prevaporized combustion system to the point of practical application to advanced gas turbine engines requires quantitative knowledge of compressor exit parameters and their effects on fuel preparation, the premixing process, and fuel droplet evaporation.

These kinds of measurements are required at steady state as well as transient operating conditions.

The effect of utilizing large quantities of front end combustion air so as to operate at ϕ's of a .5-.6 at high power in order to reduce NO_x has left little air for cooling the burner liners. The problem is further magnified by the continual development of engines that operate at increasingly high pressure levels (> 30 atm). Conventional film cooling techniques require twice the air flow that is available for maintaining conventional liner materials at acceptable temperatures. Therefore, it is extremely important that advanced cooling techniques be analyzed and developed over the next several years. Work of both an analytical and experimental nature is required to evaluate cooling techniques both thermally and structurally so that acceptable life goals can be met.

These kinds of programs may show the need for new burner liner materials in addition to the improved cooling methods. Material change to increase burner liner life and be acceptable from the standpoint of temperature gradients, manufacture cost, weight, etc., is a long-term proposition (> 10 years).

C. Summary of Recommendations

1. Study of turbulent mixing and ignition of the mixing layer between streams of premixed fuel-air and hot combustion products.

2. Study of turbulent strain induced wrinkling of flame surface and the effect of turbulent strain on flame extinction and on pollutant formation.

3. Determination of atomization and vaporization in turbulent flows characteristic of practical gas turbine combustors.

4. Establish the effect on combustor performance of large and small amplitude pressure disturbances and flow pattern distortion produced at the compressor exit or turbine inlet. Establish complete burner system transient response.

5. Establish the driving mechanisms of self-excited oscillations in primary burners, duct burners, and after-burners with a view toward their elimination or potential benefits of controlled oscillations.

6. Establish models for the apriori determination of combustor stability under small and large amplitude imposed disturbances.

7. Study the dynamics of changes in engine operating conditions on combustor performance (e.g., flame-out, flashback, autoignition), especially under near-limit performance (LPP).

8. Establish the role of catalytic combustion in future engines with emphasis on improved combustor exit temperature profile and better near-limit operation and considering the problems of catalyst life as controlled by poisoning, thermal shock, etc.

9. Establish a research program to develop or adapt various experimental techniques for combustor diagnostics with particular emphasis on: a) turbulence measurement; b) time resolved temperature, combustion, and velocity measurements under turbulent burning conditions; and c) droplet size and distribution and velocity measurements during turbulent combustion.

10. Study bluff body flame stabilization with particular emphasis on the influence of chemical and flow (turbulence) parameters. This should include investigation of spreading of the turbulent, stabilized flame.

11. Study the problem of increased cooling demands of high performance combustors, and, in turn, the effect of the use of a major fraction of the air flow for cooling on the design and performance of the combustor. This may involve the examination of advanced burner liner materials for high temperature operation.

V. COMBUSTION MODELLING

A. Introduction

The experience of the past few years in modelling complete gas turbine combustor flow fields with finite difference techniques has demonstrated that insight into the nature of the process rather than quantitative design information is the result. Qualitative trend predictions of parameters dependent on local heat release can frequently be expected. The long-term research goal should be to improve this situation by developing the modelling to provide not only insight, but quantitative design information as well. Our thoughts of an approach to meet this goal are outlined below, following a discussion of more near-term needs.

B. Research Areas

1. Near-Term Needs

Designers require model information concerning emissions and efficiency, soot and radiation heat transfer, flame stabilization and ignition (altitude relight), and pattern factor. Many of these performance parameters require more than heat release rates for characterization, and thus cannot currently be predicted correctly with the finite difference approaches. Rather, the development of simpler models which are empirical, semiempirical, modular, or of lower order dimensionality should be encouraged in the near-term as appropriate for the various performance parameters. As with the more detailed appraoches, the effects of combustor geometry and inlet conditions, as well as fuel and injector properties, should be included explicitly in the models.

In the near-term, detailed models should be used more extensively for small regions of the entire combustor flow field. Here a coupled experimental-analytical approach is recommended. Note that several of the research areas listed below require modelling of nonreacting flows and thus avoid complications presently plaguing combustion models. Also note that many of these areas can be studied in rigs providing optical access so that new diagnostic techniques, particularly Laser Doppler Velocimetry, can be employed.

Thus, in addition to development of more complete but simple correlation tools for the near-term, applied research involving detailed modelling of well instrumented experiments in the following areas is proposed:

a) Current codes which predict the air flow split through the liner dome and walls should be validated. Hole discharge coefficients should be verified for practical simulations. The effects of combustor interior velocity, annulus profiles, liner curvature, and hole configuration should be ascertained on air flow split.

b) More information is required on our ability to model the behavior of coupled and confined penetration jets. Opposed and staggered jet, and axially displaced jet interactions, in terms of penetration and mixing, are of interest. The extent of recirculation caused by interacting primary zone jets should be defined. Jet mixing in accelerating passages should be studied as well.

c) Perhaps in the way of coupling these two programs, the effects of diffuser distortions upon hot streaks (or for near stoichiometric burners fuel streaks) should be systematically explored. A can-annular system could be most susceptible to this problem, although other configurations are also of interest.

d) Finally, detailed primary zone characterization is desirable both for can and annular systems. Two-phase flow and swirl and recirculation should be included. The effects of injector design and dome and skirt configuration are of particular interest. In the annular case, the degree of interaction between adjacent injectors/swirlers as functions of the various characteristic dimensions requires determination.

In terms of priorities, programs a and b are of immediate importance. After sufficient progress, program c becomes a natural extension. Finally, because of the modelling complications (even for cold flow), program d may become appropriate.

2. Fundamental Research Requirements

The near-term research discussed above is applied, and thus it is perhaps more appropriate to expect it be performed by more applied groups at NASA or DOD. In fact, the consensus of the panel was that NASA's Combustion Fundamentals Group should concern itself with the program to follow rather than that outlined above. As noted at the beginning of this section, we believe basic research in support of our long-term modelling goals is the mission of this latter group at NASA.

We envision several programs, both experimental and including detailed modelling, to revolve around two fundamental flow fields. Initiation of these programs should be simultaneous with those discussed in the previous section. The fundamental studies should involve steady, turbulent flow in axisymmetric geometries.

a) A gas phase, elliptic flow utilizing recirculation for flame holding should be studied. First experiments might involve injection of a tracer gas in cold flow, and then a heated jet to include density variations and thermal transport. Turbulence models which correctly predict and explain the effects of anisotropy and compressibility must be developed before moving on to reacting flow cases. A model test case would be provided since local measurements of $u, v, u', v', u'v', \ldots T, T', c_j, c_j'$ will be made. Particular care should characterize the identification of initial and boundary conditions. Approach flow swirl number, inlet conditions, and configuration should be varied independently. Scaling should be checked by altering the overall size of the flow.

b) A two-phase parabolic study of spray evaporation is recommended. The experiment must be designed to involve negligible wall effects. In addition to all of the parameters identified in program a above, the following special item is unique to the two phase flow: drop size and velocity distributions must be obtained at various locations within the flow, recognizing that the specification of the initial conditions at the end of the dense spray region adjacent to the injector requires particular attention. Note that a square duct does not meet these requirements, and that other spray diagnostics (holography, fluorescence) may prove more fruitful than LDV. The capability for accurate ballistic spray modelling, including spray evaporation, must be demonstrated before moving on to the programs below. The applicability of existing single droplet modelling should be ascertained throughout. Again, a careful, well-defined experiment will provide a test case for other spray modelling efforts.

When both of the above programs have developed confidence in the fluid mechanic and two phase models, combustion would be added, as follows:

c) Premixed and unmixed combustion could be studied in program a above, and combustion in program b. Fuels should be selected for which we have confidence in modelling the chemical kinetics (H_2, wet CO, or HC $\geq C_3H_8$), all on the lean side. Now the modeler must concern himself with inclusion of turbulence-chemistry interactions, which probably must include explicitly molecular diffusion in some fashion.

Throughout all of the modelling programs suggested above, sufficient attention must be directed to the numerical analysis to positively demonstrate adequate grid resolution, convergence, and accuracy. Improvements in each of these areas should be incorporated into the models whenever possible.

There are other lower priority items which should be studied upon completion of the three programs detailed above.

d) Chemical kinetics: soot formation, liquid phase reactions; quasiglobal modelling for rich systems; and detailed kinetics to support quasiglobal modelling.

e) Multiphase flow (sprays and soot): turbulent interactions and the environments individual droplets see; the transition from ballistic to turbulent transport; soot agglomeration; the effects of turbulence on transport; turbulence generation and dissipation by drops; criteria for ignition, envelope, and wake flames.

f) Radiation: the distribution of scattering and absorption coefficients throughout the flow; absorption by the liquid fuel spray.

In summary, for development of complete detailed flow field models for combustors, a step by step set of validation experiments of increasing complexity is proposed, with a realistic starting point. The eventual goal is an accurate model for practical hardware, which will require that all of the elements discussed above be brought together in an accurate and efficient code. A more applied near-term approach is also proposed, but here nonreacting segments of the practical combustor are simulated numerically and experimentally. It is also proposed that the NASA Combustion Fundamentals Group concentrate its funding effort in the former area.

C. Summary of Recommendations

1. Develop simple models for the prediction of performance trends, and combustor sensitivity to design changes.

2. Validate current computer codes using experiments specifically designed to provide the required input data and adequate diagnostics for comparison of the model with experimental measurements.

3. Research is needed to improve the capability of modelling the behavior of coupled and confined penetration jets.

4. The effects of diffuser distortions on hot streaks should be explored.

5. A detailed characterization of the primary zone in both can and annular combustors is required to provide a base for sophisticated models and to validate models.

6. A gas phase elliptic flow utilizing recirculation for flame holding should be studied experimentally to provide a model test case.

7. A two phase parabolic study of spray evaporation and combustion is recommended to provide a basis and a test of theoretical models. These programs should be conducted under cold flow conditions to establish the fluid mechanic elements of the model and then under combustion conditions to establish the coupling with chemical reaction.

8. Studies of chemical kinetics involving soot formation, liquid phase reactions, quasiglobal kinetics of fuel rich systems are needed to support the modelling effort.

9. Turbulent interactions in two phase systems (droplets and soot) should be studied including particle-flow interactions, transition from ballistic to turbulent transport, particle agglomeration, and criteria for droplet ignition and envelope versus wake flames.

10. A thorough study of radiation effects (absorption and scattering) on combustion in two phase systems (droplets and soot) is recommended.

VI. SUMMARY

The development of advanced, high performance, gas turbine engines for modern aircraft has created a need for research on fundamental combustion problems related to modern gas turbines. A review has been made to identify the research areas of highest priority, although no effort was made to establish an order of priority within this list. Four areas were chosen as a means of organizing the review: atomization and vaporization, combustion chemistry, combustion dynamics, and combustion modelling. Other headings could have been chosen, but it became evident early in the review that the various processes occurring within the combustor are closely interrelated so that a unique set of topics could not be selected.

Much good research has been done in the field of atomization and vaporization, but the demand for improved performance complicated by the problems of limited fuel supplies, the possibility of alternative fuels, and pollution control required that advanced experimental and theoretical studies be conducted under conditions simulating the complexity of real combustors. Obviously, the chemistry and dynamics of combustion influence and are influenced by the fuel-air preparation process.

The same performance requirements dictate the need for a better understanding of the chemistry of combustion in both the liquid and vapor phase. Problems of inefficiency and the formation of soot and other pollutants requires a detailed knowledge of kinetics over a wide temperature and composition range. The problem of catalytic combustion was not listed in this portion of the review since this subject had been thoroughly reviewed in a workshop dealing with a low pollution gas turbine. This topic is listed in the section dealing with combustion dynamics.

The need for a better understanding of turbulent mixing and reaction and the various time dependent problems of flame stability, transients, and combustion oscillations are a major part of the recommendations dealing with combustion dynamics. The use of modern laboratory methods to develop diagnostic techniques for gas turbine combustors is also stressed.

Modern computing techniques have made it possible to develop sophisticated combustion models. There is a need for experiments to confirm the various components of the models and to provide a basis for continued model development.

Finally, the synthesis of the various research areas is needed to provide a comprehensive understanding of the complex interactions which govern combustor performance. These studies would permit NASA to continue its leadership in providing fundamental combustion information to the aircraft industry.

1. Report No. NASA CP-2087	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle FUNDAMENTALS OF GAS TURBINE COMBUSTION		5. Report Date
		6. Performing Organization Code
7. Author(s)		8. Performing Organization Report No. E-026
		10. Work Unit No.
9. Performing Organization Name and Address		11. Contract or Grant No.
		13. Type of Report and Period Covered Conference Publication
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

A 2-day workshop on fundamental problems related to aircraft gas turbine combustors was held on February 6 and 7, 1979, at the NASA Lewis Research Center in Cleveland, Ohio. Participants discussed combustion problems and formulated research recommendations in the areas of atomization and vaporization, combustion chemistry, combustion dynamics, and combustion modelling. This proceedings contains the recommendations considered of highest priority in these areas.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Aircraft gas turbine combustion; Atomization; Combustion; Combustion chemistry; Combustion dynamics; Combustion modelling; Fundamental combustion research; Vaporization	Unclassified - unlimited STAR Category 07

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	51	A04

* For sale by the National Technical Information Service, Springfield, Virginia 22161

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