FUNDAMENTAL CHARACTERIZATION OF ALTERNATE FUEL EFFECTS IN CONTINUOUS COMBUSTION SYSTEMS. TECHNICAL PROGRESS REPORT NO. 1, AUGUST 15, 1977--AUGUST 14, 1978

EXXON RESEARCH AND ENGINEERING CO.,
LINDEN, NJ. GOVERNMENT RESEARCH LABS

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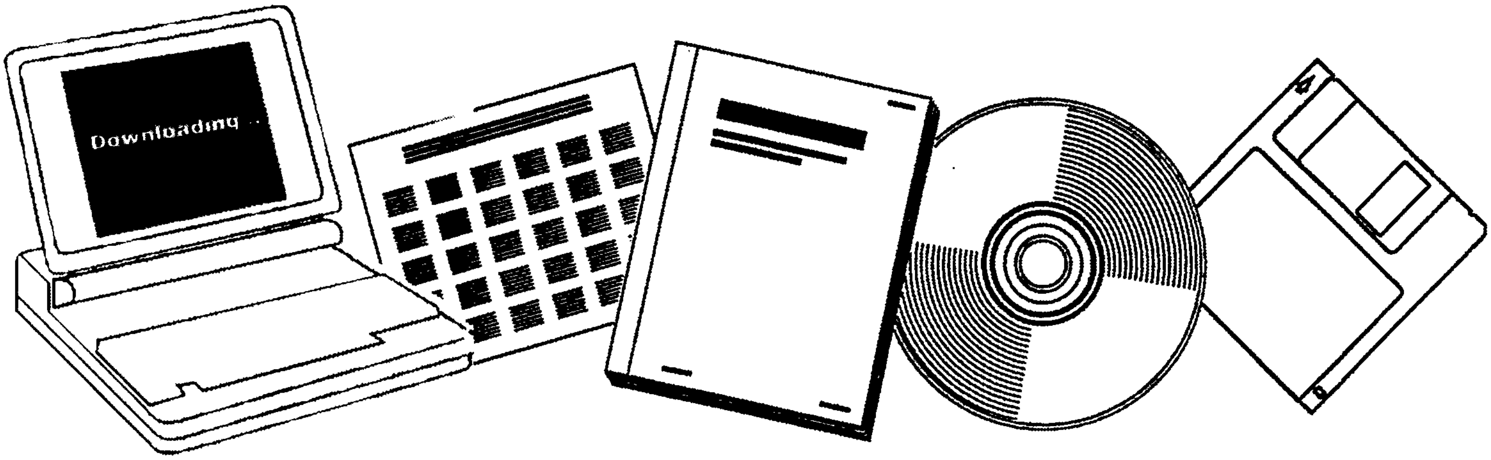

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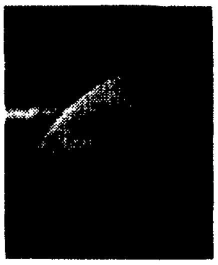

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Fundamental Characterization of Alternate Fuel Effects in Continuous Combustion Systems

Technical Progress Report No. 1

August 15, 1977-August 14, 1978

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Contract EC-77-C-03-1543

EXXON RESEARCH AND ENGINEERING COMPANY
GOVERNMENT RESEARCH LABORATORIES

FOREWORD

This is the first Technical Progress Report for DOE Contract EC-77-C-03-1543, "Fundamental Characterization of Alternate Fuel Effects in Continuous Combustion Systems". It includes background information and results for the first four months of the program. Part A concerns problem analysis and experimental description. This information has been generated by Exxon Research and Engineering Company as part of Task 1 of the first phase of this program. Portions of this information were extracted from a paper written for the DOE co-sponsored Workshop on "Alternate Hydrocarbon Fuels for Engines, Combustion and Chemical Kinetics," September 7-9, 1977. Part B concerns analytical modeling and represents efforts conducted under Task 2 of this program by Science Applications, Inc.

William S. Blazowski
Principal Investigator

SUMMARY

Alternate fuels derived from coal, oil shale, and tar sands are expected to play an increasingly important role in meeting the future national energy demand. The properties of these fuels can result in significantly different combustion performance compared with conventional specification fuels. For example, decreased hydrogen content can result in increased flame luminosity and exhaust smoke emissions, higher fuel bound nitrogen can result in increased NO_x emissions, and fuel impurities can result in deposition within the combustion device. Although additional refining and fuel treatment can mitigate these problems to some extent, the approach of adapting the combustion system to utilize fuels having "unconventional" properties while operating in an environmentally acceptable manner seems to be most cost effective and energy efficient. This program will provide vital fundamental information necessary for the efficient pursuit of this approach.

The subject program is a multi-year effort to provide an improved fundamental understanding of the relationships between fuel properties and combustion characteristics and to develop analytical modeling/correlation capabilities for the prediction of fuel effects. The work will be limited to investigation of alternate liquid and gaseous fuels used in continuous combustion systems, with gas turbine systems receiving special attention. The program philosophy is to relate fundamental combustion phenomena to fuel characteristics using analytical models developed with and eventually verified by data obtained in carefully designed experiments. Consequently, the program will proceed along two parallel paths, modeling and experimental. ER&E will be responsible for overall program direction and experimentation, while Science Applications, Inc. (SAI) will be responsible for analytical modeling under subcontract to ER&E.

Effort during the first phase of this program will provide a well-developed plan for subsequent years of the program. Key combustion properties and ranges of fuel variation of interest to our subsequent efforts have been surveyed. Recently initiated experimental work includes the utilization of unique ER&E experimental equipment for evaluation of fuel combustion characteristics. The analytical modeling effort includes new applications of quasi-global modeling techniques as well as predictions of and comparisons with the experimental results generated. Efforts during the second two years of this program will concentrate on solving the problems identified using the approaches defined in Phase 1. These efforts will be characterized by the broad application of experimental combustion facilities available at ER&E. The SAI modeling work will not only attempt to better define chemical and physical phenomena, but will also provide valuable guidance concerning the design of experiments. This cooperative, iterative procedure will optimize the improvements to fundamental understanding and the generation of an analytical model during this program.

This report is intended to provide background information which describes the current understanding of alternate fuel effects in gas turbines. From this discussion, the key technical areas requiring additional study and analysis will be identified and prioritized. Current plans for experimental study of the highest priority problem, soot formation, will be briefly reviewed. A survey of appropriate analytical modeling capability has been conducted and is also reported in Part B. Discussions are divided into four sections: computational methods for recirculating reacting flows, turbulent flow modeling and the phenomena of unmixedness, droplet and spray combustion, and fuel decomposition and combustion.

PART A: PROBLEM ANALYSIS AND EXPERIMENTAL DESCRIPTION

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PART A

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I. INTRODUCTION

With increased emphasis on the utilization of U.S. energy resources for national self-reliance, alternate (synthetic) fuels are expected to play an important role in future energy developments. The major North American resources from which future synthetic fuels (synfuels) will be derived are coal, shale, and tar sands deposits. Fuels derived from these resources will include coal liquids, methanol, and low, intermediate, and high BTU coal gas products as well as hydrocarbon liquids derived from oil shale and tar sands.* While the liquid fuels are expected to replace the continually diminishing supply of petroleum products, the characteristics of these synfuels are not yet defined.

Even before the significant appearance and usage of synfuels, the characteristics of petroleum-derived fuels can be expected to undergo some change. As petroleum availability declines and as previous large consumers utilize other resources, market competition may cause fuel variation within specifications and may even result in significantly increased requests for specification waivers. In addition, production from new locations (i.e. the Alaskan North Slope, North Sea, and U.S. offshore areas) may yield crude with characteristics which further aggravate the situation.

These future changes in fuel characteristics will affect energy consumers differently. In stationary applications, where significant non-petroleum energy is already utilized, widespread conversion to the usage of coal from oil is anticipated. While new exhaust emissions control technologies must be developed to accomplish this task in an environmentally acceptable manner, the engineering know-how to utilize coal and experience previously developed can be expected to facilitate conversion. Transportation applications, however, present a much more difficult problem. Nearly all fuels currently used in these applications are petroleum-derived and significant variations in fuel character have not been previously experienced.

It is most likely that a liquid hydrocarbon fuel will continue to be necessary for the more fuel-sensitive transportation applications. Difficulties which may soon be experienced in utilizing expanded specification petroleum-derived fuels will eventually yield to the more severe requirements associated with synfuel usage. The synthetic fuels are significantly different from traditional petroleum-derived fuels. Synfuels, especially those derived from coal, will be more aromatic and have significantly decreased hydrogen content. These characteristics can be expected to result in increased soot formation, increased flame radiation (which can affect the integrity of combustor hardware), and increased deposit forming tendency, possibly resulting in plugging and fouling of equipment. Another significant difference between conventional petroleum and synthetic crudes is nitrogen content. Depending on the extent of refining performed, increased NO_x emission from fuel bound nitrogen may also be a problem. Finally, as a result of the generally lower volatility of synthetic crudes, synfuels might be expected to be less volatile than petroleum-derived fuels thereby causing problems associated with fuel droplet burning.

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* Limited synfuel production from tar sands is already a reality, but this resource is small compared to the potential of coal or oil shale reserves.

Optional approaches for the utilization of synfuels and/or petroleum-derived fuels in the future consist of energy-intensive refining steps to match conventional fuel specifications or devising ways of altering combustion systems to allow combustion of fuels not meeting current specifications. In his plenary session paper "Synthetic Fuels and Combustion" at the 16th International Combustion Symposium, J. P. Longwell of Exxon Research and Engineering Company discussed the rationale for the utilization of synthetic liquid fuels without extensive refining. The incentives for following this route were shown to be very significant from the standpoints of energy conservation and cost.

For the transportation system designer, the task at hand is one of evaluating the impact of changes in fuel character and defining the range of fuel characteristics within which the system can operate. The U.S. Air Force has initiated one such program for defining future military aircraft fuels. The combustion effects of future fuels are to be characterized along with other system factors (e.g., fuel tank design, pumps, handling requirements, etc.) and fuel processing information is to be acquired. A trade-off analysis will then determine the characteristics (a future fuel specification) which will result in minimum total operating cost and adequate availability without significant sacrifice in safety, performance, or environmental impact. With respect to availability, geographic variability in the staple resource and in refining capability will cause combustion system flexibility to be an important asset. Future development of "fuel flexible engines" may receive high priority, especially for military applications.

Indeed, each application to utilize future synfuels or expanded-specification petroleum fuels must develop such a program. It is anticipated that the outcome of such studies will be the realization that future fuels should be significantly different than those now in use. Naturally, these findings should strongly influence future synfuel process design.

Regardless of the application, the impact of the fuel on the combustion system would be expected to play the major role. Unfortunately, the investigation of fuel impact on combustion systems is almost entirely empirical and expensive, large-scale testing is necessary. Our current understanding of the fundamental combustion phenomena which influence a fuel's practical combustion characteristics is extremely limited. The extensive efforts to develop combustor models during the past decade have avoided the complexity of input details which would define fuel characteristics and the existing ability to predict, or even extrapolate, fuel effects is nearly non-existent.

The current situation, although understandable in light of the previous assumed availability of low-cost fuel of consistent high quality, must now be corrected. Fundamental understanding of the combustion phenomena influencing a fuel's performance (gas phase fuel pyrolysis kinetics, soot formation and oxidation, droplet evaporation and combustion, and aerodynamic/chemical interactions) must be developed. Further, models to be used by the combustion system designer for prediction of fuel effects in real systems (i.e., means to utilize the details discussed above) are required.

This program addresses the serious weakness in our ability to fundamentally relate fuel characteristics to combustion effects. The end product of the program will be an imporved fundamental understanding of fuel effects and analytical models for the prediction of fuel effects based on data acquired in carefully designed experiments. These tools will be of invaluable assistance to combustor designers in both the near term, where the impact of variations in the characteristics of petroleum-derived fuels are of concern, and mid to long term applications, where synfuels will be utilized and fuel flexible engines will be desired.

While the information derived in this program may be broadly applicable, it is not possible to address directly all types of combustion systems within the current program scope. The work will concentrate on continuous combustion systems, which are known to be the most fuel flexible, thereby anticipating future demands for fuel flexibility. Particular emphasis will be placed on gas turbine systems, as they constitute a well-defined application of continuous combustion and represent a significant and increasing portion of transportation energy consumption. References 1-16 discuss future gas turbine fuels developments.

Consistent with this orientation, the following sections address gas turbine combustion systems, fuel effects on gas turbines combustion systems, and changes for fuel flexibility. Based on this information a matrix of fuel characteristics and combustion phenomena requiring study have been developed. These are described in Section V. Present plans to study soot formation through the use of the jet stirred reactor are discussed in Section VI. The References and Bibliography Section includes the numbered references cited in Part A as well as a more extensive listing of information sources uncovered in literature searches conducted during this program.

Portions of this text have been extracted from a paper written for the SQUID Workshop on "Alternate Hydrocarbon Fuels for Engines: Combustion and Chemical Kinetics", September 7-9, 1977 at Columbia, Maryland. This DOE co-sponsored event included discussions on a number of different engine types but aircraft turbines received special attention. As a result of this emphasis the following sections relate closely to the aircraft gas turbine application. This orientation is beneficial in a number of respects. First, the aircraft industry provides much of the advanced technology for other gas turbine applications; focusing on the aircraft application allows the most advanced technology to be considered. Secondly, it is beneficial to consider the problem of alternate fuel usage within the constraints posed by system design requirements (e.g. size, weight, etc.). In the sections which follow these requirements are outlined and their impact or our ability to achieve more fuel flexible designs will be evident.

II. THE GAS TURBINE COMBUSTION SYSTEM

The gas turbine employs the Brayton thermodynamic cycle -- adiabatic compression, constant pressure heat addition, and adiabatic expansion. The function of the combustion system is to accomplish the heat release with complete combustion and minimum pressure loss and to satisfy numerous engine operational requirements. This section describes the type of hardware used and the requirements which must be satisfied.

A. Description

Turbine engine combustors have undergone continuing development over the past 40 years resulting in the evolution of a variety of basic main combustor configurations. Contemporary aircraft combustion systems may be broadly classified into one of the three types schematically illustrated in Figure 1.

The function of the main burner is to provide for the mixing of fuel and air within the proper environment to ensure their nearly complete reaction to desirable combustion products. Operation of can, cannular, and modern annular combustors is adequately described through consideration of Figure 2. In the "primary zone", fuel and oxidizer are mixed, usually in slightly fuel-rich proportions. Approximately 90 percent of the fuel is burned in this zone. Fuel oxidation is completed in the "secondary zone". In modern engines, turbine inlet temperatures are close to the temperature at which significant chemical reactions cease ($\sim$1600°K) and no dilution is required. However, older designs with reduced turbine inlet temperatures utilize a "dilution zone" to further reduce temperature. No significant reaction occurs within this zone.

The fuel-air ratio typically required for the combustor temperature increase is less than one-third the stoichiometric quantity -- that resulting in complete O_2 consumption upon fuel conversion to CO_2 and H_2O. The equivalence ratio parameter, ϕ, defined as the ratio of the actual fuel-air mixture strength to that required for stoichiometric combustion, provides a convenient way of describing mixture variations through the combustor. Current primary zone equivalence ratios are about one whereas combustor exit values are less than one-third.

The purpose of the primary zone is to stabilize combustion. High temperatures resulting from stoichiometric operation promote rapid fuel consumption reactions. Primary zone flow is dominated by a strong recirculation region (established by swirling the air entering the head end or dome of the burner) which furthers combustion stability. The requirement to ensure an adequate residence time for completion of chemical reactions is satisfied by limiting combustor reference velocity (the average cold-flow velocity just behind the primary zone) to about 25 m/sec.

In practically all current gas-turbine combustors, the fuel is injected as a liquid. The formation of a well distributed dispersion of small droplets is desirable to promote rapid evaporation of the fuel and intimate mixing of the fuel and air. Two general categories of fuel injectors

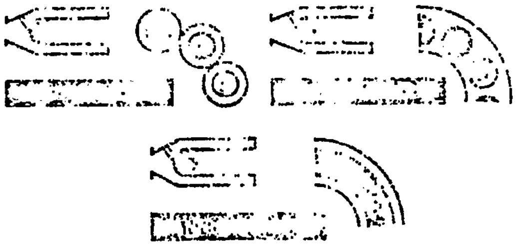


Figure 1: Types of Combustion Systems

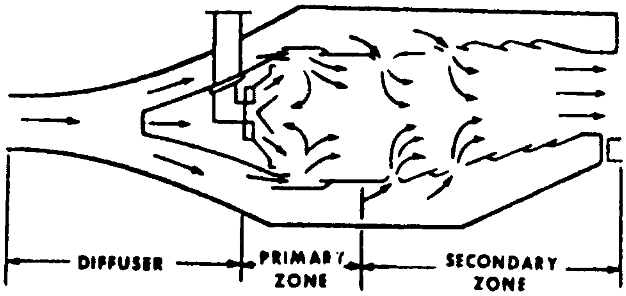


Figure 2: Conventional Main Combustor

are currently employed. Pressure atomizers utilize a large fuel pressure drop (greater than 100 psi) across a nozzle to create a finely dispersed spray of small ($<50\mu$) fuel droplets which quickly vaporize. Airblast atomizers create strong swirling motions of a small portion of the combustor air flow into which fuel is introduced. The severe shearing motion of the air disperses the fuel and results in small fuel droplets.

The secondary zone introduces additional air to provide for the chemical reactions which consume the products of incomplete combustion passing from the primary zone. Air participating in these chemical reactions is introduced normal to the main flow direction. The remaining air enters parallel to the main flow at the combustor walls to provide a film of cool air which protects the combustor liner and to tailor the temperature profile exiting the combustor. Design of the combustor liner hole pattern to accomplish this requirement traditionally involves a costly development effort to avoid a number of possible detrimental effects. Excessive addition of air may result in quenching chemical reactions (especially carbon monoxide and soot oxidation) essential in reducing emissions. Air introduction must be accomplished in a manner which results in the correct temperature profile entering the turbine; a 25 K increase in temperature at a critical region of a turbine blade can result in a four-fold decrease in blade life. These design objectives must be met within a prescribed combustor length. Although increasing combustor size might facilitate the design task, this would cause undesirable increases in engine length, main shaft size, bearing requirements and engine weight.

Combustor liners must be designed for high structural integrity to support forces resulting from pressure drop and must have high thermal resistance capable of continuous and cyclic high temperature operation. This is accomplished through utilization of high strength, high temperature oxidation-resistant materials and effective use of cooling air. Depending upon the temperature rise requirements of the combustor, 20-50 percent of the inlet airflow may be utilized in liner cooling. A number of conventional cooling techniques are illustrated in Figure 3.

a. Louver Cooling--Many of the early jet engine combustors used a louver cooling technique in which the liner was fabricated into a number of cylindrical panels. When assembled, the liner contained a series of annular air passages at the panel intersection points, the gap heights of which were maintained by simple wiggle-strip louvers. This permitted a film of air to be injected along the hot side of each panel wall providing a protective thermal barrier. Subsequent injection downstream through remaining panels permitted replenishment of this cooling air boundary layer. Unfortunately, the louver cooling technique did not provide accurate metering of the cooling air which resulted in considerable cooling flow nonuniformity with attendant variations in combustor exit profiles and severe metal temperature gradients along the liner.

b. Film Cooling--This technique is an extension of the louver cooling technique but with machined injection holes instead of louvers. Consequently, airflow metering is more accurate and uniform throughout the combustion chamber. Most current combustors use this cooling technique. However, increased operating gas temperatures of future combustors will result in less air for cooling and more advanced cooling techniques/materials will be required.

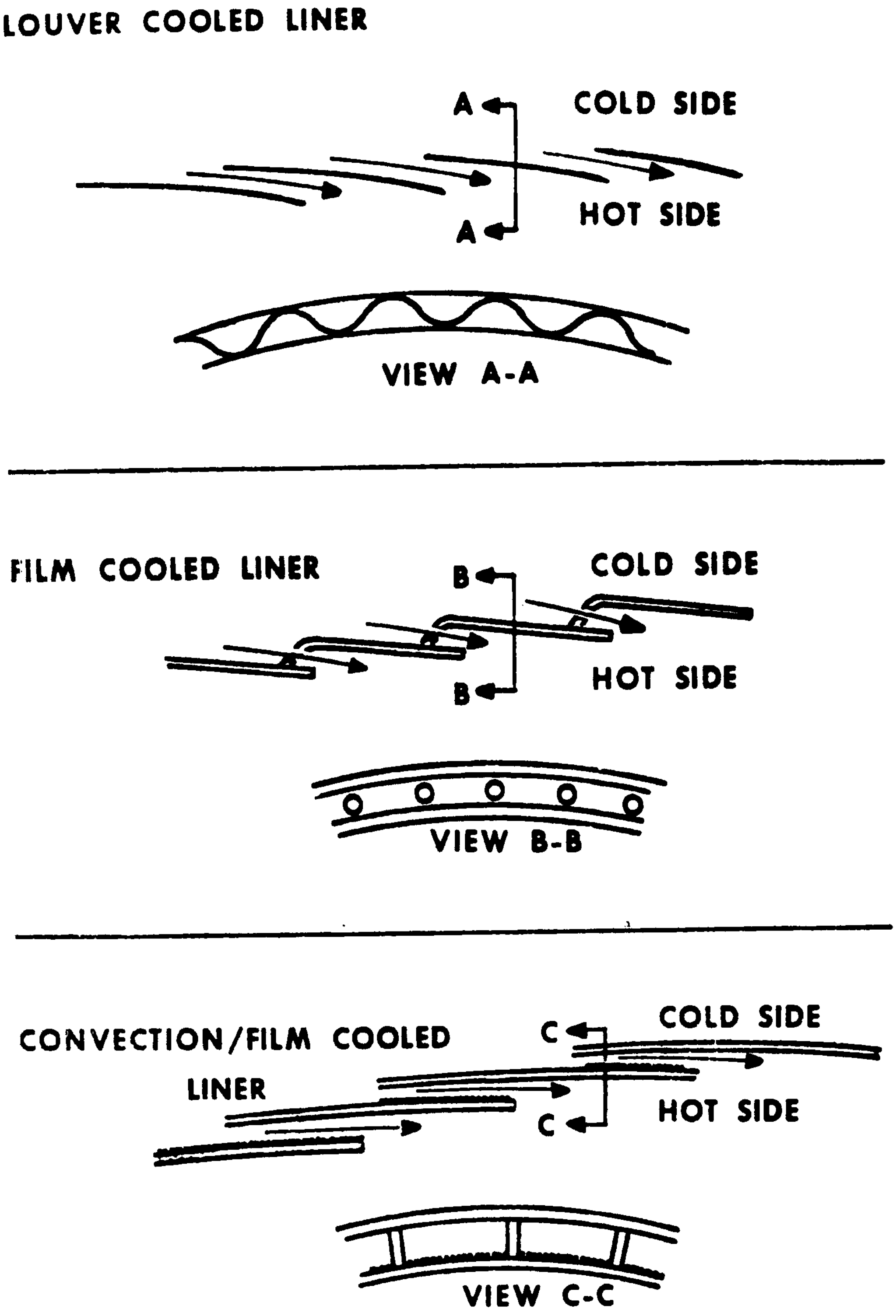


Figure 3: Conventional Combustor Liner Cooling Techniques

c. Convection/Film Cooling--This relatively new technique developed by Detroit Diesel Allison Division of General Motors permits much reduced cooling air flow (15-25 percent) while providing high cooling effectiveness and uniform metal temperatures. It is particularly suited for high temperature rise combustion systems where cooling air is at a premium. The convection/film cooled liner takes advantage of simple but controlled convection cooling enhanced by roughened walls while providing the protective boundary layer of cool air at each cooling panel discharge plane. Although somewhat similar in appearance to the louver and film cooled liners, the convection/film coolant passage length is several times greater; more accurate coolant metering is provided and a more stable coolant film is established at the panel exit. Principal disadvantages of this design are somewhat heavier construction, increased manufacturing complexity and repairability difficulties.

B. System Requirements

A broad list of combustion system performance and design objectives is required of all combustors. Although this list can be quite lengthy, the more important requirements, some of which were alluded to above, are discussed below; these focus on the aircraft application but are adaptable to the industrial/utility turbine combustors with obvious modifications which recognize ground utilization.

- Performance Objectives
  a. High combustion efficiency (100%) at all operating conditions.
  b. Low overall system total pressure loss.
  c. Stable combustion at all operating conditions.
  d. Reliable ground-level ignition and altitude relight capability.

- Design Objectives
  e. Minimum size, weight, and cost.
  f. Combustor exit temperature profile consistent with turbine design requirements.
  g. Good durability, maintainability, and reliability.
  h. Minimum exhaust emissions consistent with current specified limitations and regulations.

These demands are discussed in more detail in the following subsections.

a. Combustion Efficiency: Since propulsion system fuel consumption has a direct affect on aircraft system range, payload and operating cost, it is imperative that design point combustor efficiency be as close to 100% as possible. Combustion efficiency at the high power/high fuel consumption conditions of take-off and cruise is always near 100% (usually greater than 99.5%). However, off-design efficiency, particularly at idle, can be in the low nineties.

b. Overall Pressure Loss: The combustion system total pressure loss from the compressor discharge to the turbine inlet is normally expressed as a percent of compressor discharge pressure. Losses of 5-8% are typically encountered in contemporary systems. Combustion system pressure loss is recognized as necessary to achieve certain design objectives (pattern factor, effective cooling, etc.) and can also provide a stabilizing effect on combustion aerodynamics. However, pressure loss also impacts engine thrust and specific fuel consumption. Each additional percent increase in pressure loss will result in approximately a 1% decrease in thrust and a .5-.75% increase in specific fuel consumption. Consequently, design goals for pressure loss represent a compromise among the above factors.

c. Combustion Stability: Combustion stability is defined as the ability of the combustion process to sustain itself in a continuous manner. Stable, efficient combustion can be upset by the fuel-air mixture becoming too lean such that temperatures and reaction rates drop below the level necessary to effectively heat and vaporize the incoming air and fuel. Such a situation causes blowout of the combustion process. In addition to these extinction considerations, oscillatory combustion -- sometimes called acoustic instability -- must be avoided.

d. Ignition: Ignition of a fuel-air mixture in a turbine engine combustor requires inlet air and fuel conditions within flammability limits, sufficient residence time of the potentially burnable mixture, and the location of an effective ignition source in the vicinity of the burnable mixture. Reliable ignition in the combustion system is required during ground-level startup and for relighting during altitude windmilling. The broad range of combustor inlet temperature and pressure conditions encompassed by a typical ignition/relight envelope is illustrated in Figure 4. It is well known that ignition performance is improved by increases in pressure, temperature, fuel-air ratio, and ignition-source energy. In general, ignition is impaired by increases in reference velocity, poor fuel atomization, and low fuel volatility.

e. Size, Weight, Cost: The main combustor of a turbine engine, like all other main components must be designed within constraints of size, weight, and cost. The combustor diameter is usually dictated by the engine casing envelope provided between the compressor and turbine and is never allowed to exceed the limiting diameter defined for the engine. Minimization of combustor length allows reduction of engine bearing requirements and permits substantial reductions in weight and cost. Advancements in design technology have permitted major reductions in combustor length. With the advent of the annular combustor design, length has been reduced by at least 50% when compared to contemporary cannular systems.

f. Exit Temperature Profile: A critical turbine-life-determining parameter controlled by the combustor design related to the temperature uniformity of the combustion gases as they enter the turbine. In order to ensure that the proper temperature profile has been established at the combustor exit, combustion gas temperatures are often measured by means of high temperature thermocouples or via gas sampling techniques employed at the combustor exit plane. A detailed description of the thermal field entering the turbine both radially and circumferentially can be determined from this data.

g. Durability, Maintainability, Reliability: A principal combustor design objective is to provide a system with sufficient durability to permit continuous operation for an acceptably long time period between scheduled major engine overhauls, at which time it becomes cost effective

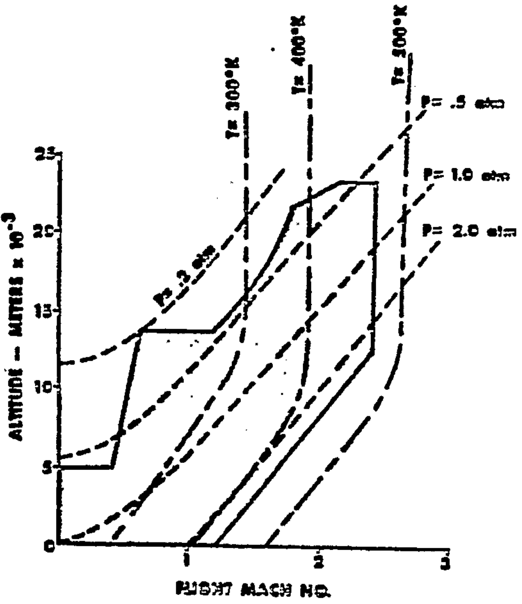


Figure 4. Ignition/Relight Envelope

to make necessary repairs and/or replacements. In the case of the main burner, durability is predominantly related to the structural and thermal integrity of the dome and liner. The combustor must exhibit good oxidation resistance and low stress levels at all operating conditions if durability is to achieved.

A maintainable component is one that is easily accessible, repairable, and/or replaceable with a minimum of time, cost, and labor. While most combustor liners can be weld repaired if damaged or burned, turbine removal is required for replacement of combustors in many cases. Combustor cases and diffuser sections require minimal maintenance and fuel nozzles and ignitors can generally be replaced and/or cleaned with minimal effort.

Reliability can be defined as the probability that a system or subsystem will perform satisfactorily between scheduled maintenance and overhaul periods. Component reliability is highly dependent on the aircraft mission, geographical location, and pilot operation since these factors strongly affect the actual combustor temperature-pressure environment and cyclic history of the components. In that the combustor has virtually no moving parts, its reliability is strongly related to fuel nozzle and ignitor performance. While fouling and carboning of these subcomponents are common causes for engine rejection, these problems are relatively easy to correct through normal inspection and replace field maintenance procedures.

h. Exhaust Emissions: With the advent of environmental regulations and goals for aircraft gas turbine systems (17,18), the levels of carbon monoxide (CO), unburned hydrocarbons (HC), oxides of nitrogen (NO_x) and smoke in the engine exhaust become important. Naturally, the environmental constraints directly impact the combustion system -- the principal source of nearly all pollutants emitted by the engine. Major changes to combustor design philosophy have evolved in recent years to provide cleaner operation at all conditions without serious compromise to engine performance. Further emissions reductions are being sought in efforts such as the NASA Experimental Clean Combustion Program, ECCP (19-21).

CO and HC are the products of incomplete combustion in a gas turbine system. At design conditions -- near full load or at cruise conditions -- both of these emissions are negligible. However, during engine idle conditions when combustor inlet temperatures and fuel-air ratios are low, combustion efficiency decreases and CO and HC emissions increase. Techniques to minimize these emissions focus on control of fuel-air distribution at idle to optimize temperature and residence time conditions to provide for maximum combustion efficiency.

NO_x emissions from continuous combustion process result from three formation mechanisms. The best understood mechanism involves "thermal NO" which arises primarily from combination of N_2 and O present during combustion at near stoichiometric conditions. N_2 and O equilibrium concentrations can be utilized to predict thermal NO. While "prompt NO" may result from similar chemical reactions, this second mechanism is not predictable by equilibrium concentration assumptions. Prompt NO is formed at the very beginning of the combustion process and is thought to be associated with active radical concentration levels far in excess of equilibrium formed during the fuel pyrolysis and chain branching which initiates the combustion process. The third and final mechanism for NO formation is that where nitrogen chemically bonded to the fuel is converted to NO_x. Fuel nitrogen has been found to be very effectively converted to NO_x (30-100% conversion) in laboratory studies and in actual gas turbine combustion testing. This mechanism for NO_x formation is thought to be very rapid, occurring early in the combustion process during fuel pyrolysis.

The importance of each of these three contributions in gas turbine combustors is illustrated in Figure 5. An assumed fuel nitrogen concentration of 0.3% and a 100% conversion efficiency have been used in developing this figure. Thermal and prompt NO_x values were determined with the analytical correlation of Reference 22. At low power, combustion inlet temperature corresponding to large engine idle or small (<1000HP) engine operation, fuel nitrogen is the predominant contribution followed by prompt and then thermal NO_x. At high inlet temperature operation, corresponding to stationary or aircraft high-power conditions, thermal NO is the primary contribution followed by fuel NO_x and finally, prompt NO_x. It should be noted that current aircraft jet fuels have fuel nitrogen contents far below this level (usually less than 20 ppmw) and NO_x from fuel nitrogen is not a present concern.

Smoke is formed at higher power conditions when the primary zone of the combustor operates with its highest fuel-air-ratio. The carbon particle formation processes which occur in the primary zone and the limits of soot formation will be described in Section IV A.1. Techniques which have been employed to reduce smoke emission depend on the introduction of additional air into the primary zone (to achieve leaner operation) and the improvement of mixing to avoid rich fuel-air pockets (23-28).

Beyond the difficulty of exhaust visibility is the ill-defined issue of the health effects of emitted particulates. While there has been some general discussion of the effects of humans of particulates of various size ranges, none of the existing regulations address this potential problem. It should be noted that some limited work has indicated the possibility that carcinogenic compounds may be present in gas turbine emitted particulates (29).

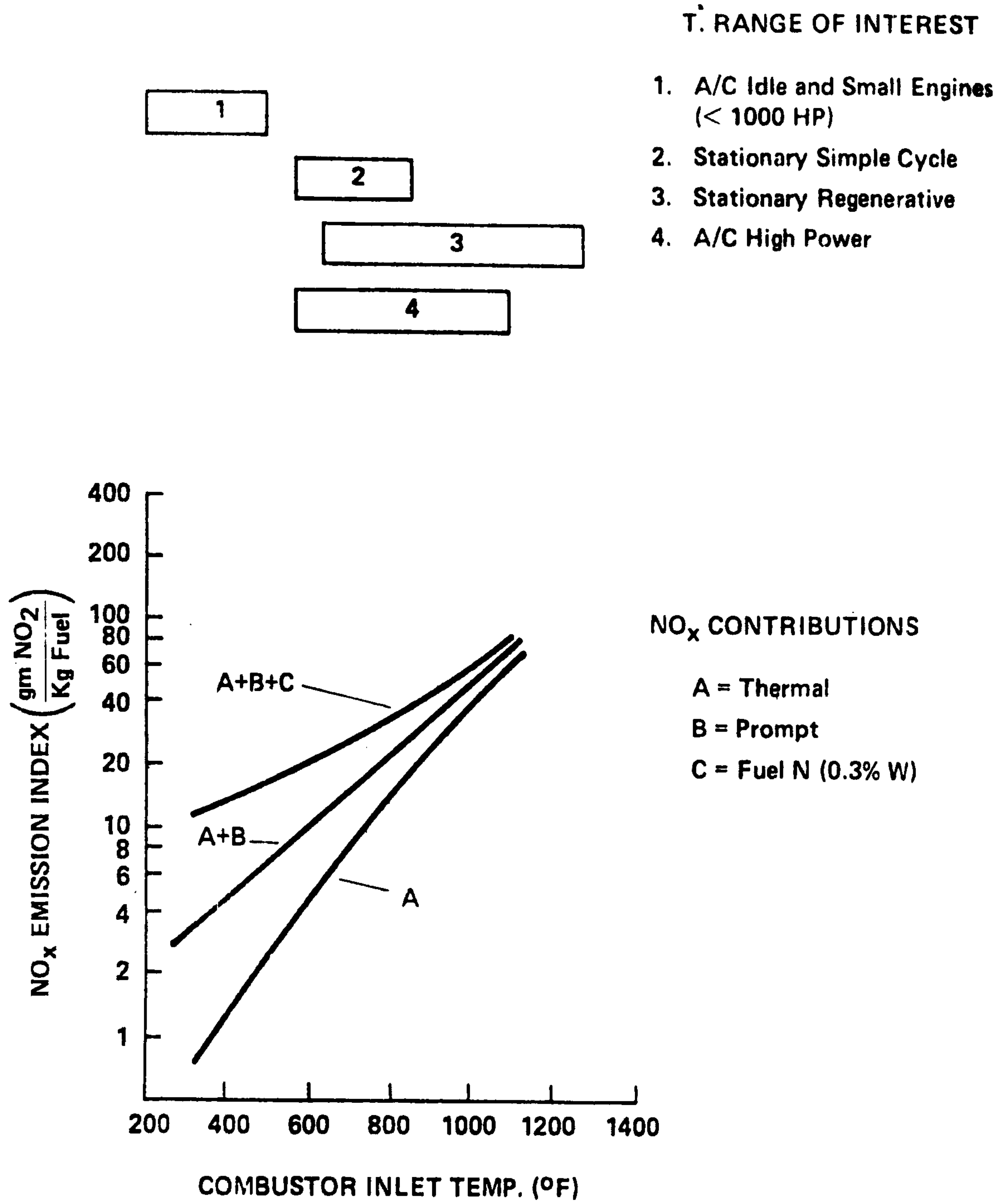


Figure 5: NO_x Mechanisms in Gas Turbine Combustion

III. FUEL EFFECTS ON COMBUSTION SYSTEMS

Fuel characteristics which are most likely to affect the gas turbine combustor designer in the future are fuel hydrogen and nitrogen content and fuel thermal stability. In addition, the designer may be confronted with changes in fuel characteristics influencing volatility, viscosity, sulfur, and trace metal content. Each of these topics is discussed below.

A. Fuel Hydrogen Content

The impacts of reduced fuel hydrogen content are associated with increased rates of carbon particle formation. Effects include increased flame luminosity leading to higher combustion liner temperatures and increased smoke emission. The following subsections focus on the carbon particle formation process, smoke emission dependence on hydrogen content and the effects of increased flame luminosity.

1. The Carbon Particle Formation Process

While both carbon formation and carbon consumption processes occur in continuous combustion systems, the latter are very much slower. The optimum approach for preventing hardware distress and avoiding serious environmental consequences is to develop technology to avoid carbon formation while satisfying other system requirements (efficiency, gaseous emissions, hardware reliability, etc.).

The predominance of fundamental research activity has involved laminar premixed flames. Street and Thomas' work published in 1955 is extremely thorough in experimental detail and breadth of hydrocarbons examined (30); it has become the classical paper in the field. Other publications are References (31-42). These investigations have universally confirmed that soot formation is a kinetically controlled process. Equilibrium calculations indicate that soot should not be present at fuel-air mixture conditions where the oxygen-to-carbon atomic ratio (O/C) is greater than one. That is, the general chemical equation

$$C_xH_y + \frac{x}{2} O_2 \rightarrow XCO + \frac{y}{2} H_2$$

should define a soot formation threshold. All experimental results have shown soot formation at O/C substantially in excess of unity.

Another very important premixed flame experiment conducted at the British National Gas Turbine Establishment (NGTE) attempted to evaluate the effect of pressure on soot formation (37). All previously mentioned work with premixed flames concerned atmospheric or sub-atmospheric conditions. The combustion system employed took special precautions to prevent flashing back to upstream locations, an additional difficulty associated with the high pressure operation. In addition to sooting limits, the amount of soot formed was determined and expressed as a "soot formation ratio" (the percent of fuel carbon evident as soot). The index of the soot quantity was found to increase with the cube of pressure. Very useful plots of pressure versus equivalence ratio for various values of soot formation ratio were presented. Examples are shown in Figure 6 for cyclohexane, cyclohexene, and benzene. Gas phase species were also determined during this testing and it was concluded that H_2O and CO_2 (oxygenated compounds not predicted by equilibrium for the system ($C_xH_y + \frac{y}{2} O_2 \rightarrow XCO + \frac{y}{2} H_2$) are formed in substantial quantities and deplete the system of oxygen prior to consumption of all fuel.

Soot formation in laminar diffusion flames has also been studied (43-46). The direct utility of this information for the gas turbine combustion application has been questioned, as the mixing rates and characteristic times for chemical reaction are very much different than those in the typical combustor. Shirmer (47) has discussed the significant differences between such experiments and the actual combustion process. He is particularly critical of the use of the smoke point test as an index of fuel tendency to form carbon particulates. Turbulent diffusion flame results would appear to be more applicable (48). Wright (46) has examined soot formation in a diffusion flame burner and has published results of soot measured when the fuel side of the flame is supplemented with oxygen at concentrations well below O/C = 1. Surprisingly, it was found that the addition of oxygen increases soot formation up to an optimal rate at which the influence abruptly reverses and soot suppression is accomplished at higher O_2 concentrations.

Wright's work involving soot formation in the jet stirred reactor (49,50) is perhaps of most interest to this discussion -- it is a combustion process similar to that at which soot forms in the primary zone of an actual continuous combustion system. As in the previously mentioned studies, it was determined that soot forms at O/C > 1 but the strong backmixing of the jet stirred reactor did afford some broadening of the soot-free O/C ratio. In addition to the establishment of sooting limits, as determined by the color of the flame (luminous yellow versus blue), Wright determined the concentrations of soot formed for some limited conditions of O/C below the soot limit. No analysis of this "yield" data to determine soot formation kinetics was undertaken but it is recognized that more such data might provide the basis for global carbon formation chemical models.

The key fundamental data discussed above have been summarized in Table 1. These results indicate that all hydrocarbons soot at O/C > 1. The table also illustrates broadened soot limits afforded by backmixing in the jet stirred reactor. Figure 7 illustrates the difference in soot production between the jet stirred reactor and a premixed laminar flame (50). Since the troublesome aromatic compounds are present in relatively small amounts in practical fuel blends, the fuel-air ratio to achieve the design temperature rise is dominated by the balance of the fuel composition which may be relatively high in hydrogen content. Therefore, the fuel-air mass ratio for incipient soot formation is most important to the combustor designer. This information based on the jet stirred reactor sooting limits (49), has also been included in Table 1. The fuel-air ratio representation emphasizes the soot forming tendencies of the aromatic type compounds. Consequently, attempts to utilize reduced hydrogen content fuels with increased aromatic compounds would be expected to experience the difficulties associated with soot formation.

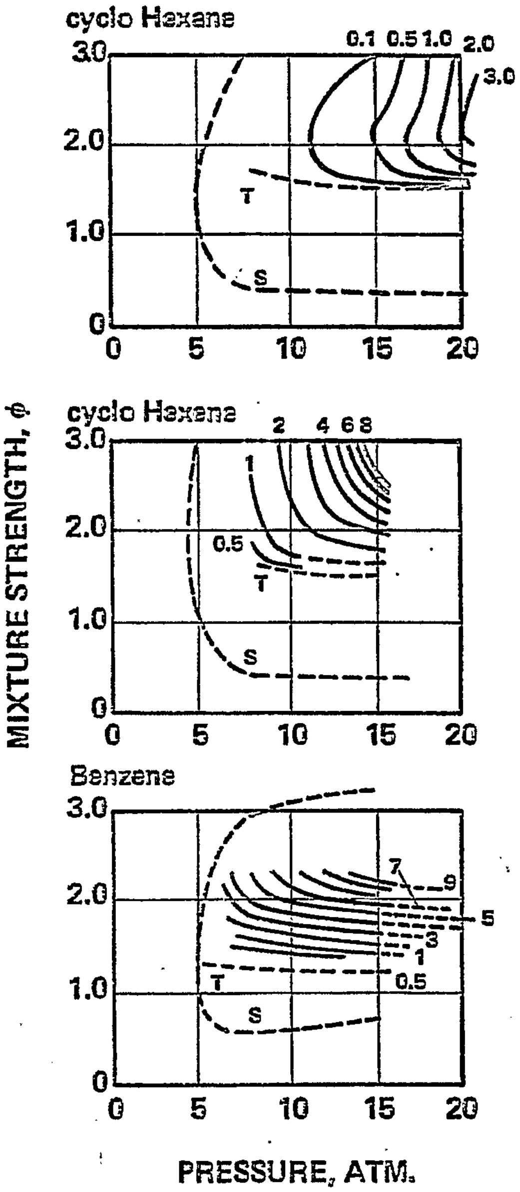


Figure 6: Effect of Pressure and Mixture Strength on Soot Formation (S denotes flame stability limit, T the soot formation threshold, and numbers indicate conditions producing a constant "soot formation ratio") From Reference 37.

Table 1. Carbon Formation Limits for Various Fuels

	Critical O/C Ratio for Incipient Carbon Formation		f/a Mass Ratio for Carbon Formation at Well-Stirred Conditions
Fuel	Pre-Mixed Bunsen Flame	Well-Stirred Condition	
	(from Reference 30)	(from Reference 49)	
Ethane	2.10	<1.56	>0.140
Propane	2.14	<1.41	>0.151
Hexane	2.18	<1.75	>0.119
Ethylene	1.67	1.43	0.1426
Propylene	1.79	1.40	0.146
Butene	2.08	1.48	0.138
Benzene	1.75	1.75	0.116
Toluene	1.92	1.71	0.112
Xylene	2.08	1.80	0.107
Tetralin	2.27	1.81	0.106
1-Methyl napthalene	2.38	1.62	0.116

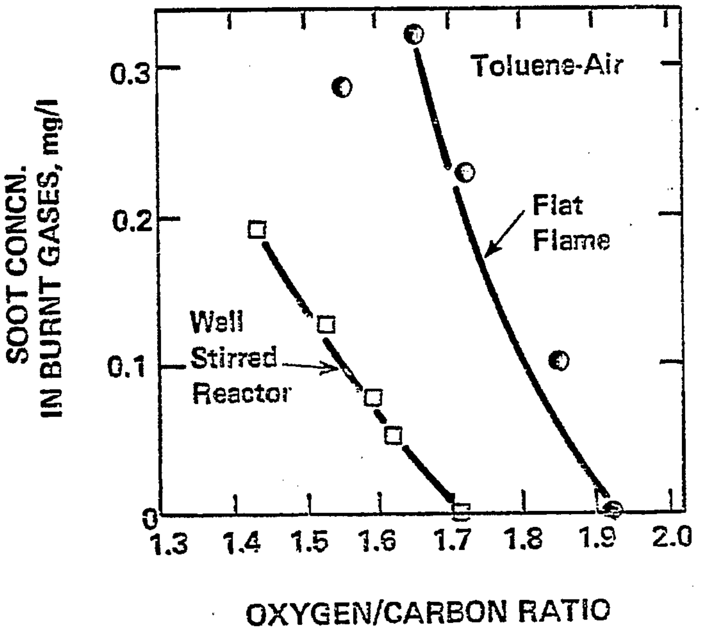


Figure 7: Soot Production in Laminar and Backmixed System for a Toluene-Air Flame (Reference 50).

2. Smoke and Particulate Emission Effects

Reductions in fuel hydrogen content can severely handicap the designer in his goal of attaining exhaust invisibility. Figure 8 illustrates the relationship between smoke emission and fuel hydrogen content. These data were acquired at a combustor inlet temperature of 756°K using a T56 single combustor rig (51). Substantial increases in the SAE Smoke Number (SN) -- determined from the reflectance of a smoke spot formed on filter paper after passing a known volume of exhaust sample (52) -- with decreasing hydrogen content are noted at each combustor inlet temperature. These changes can cause serious visibility problems in engines with current SN values near the visibility threshold (depending on engine size the threshold varies from SN = 20 to 40). Further, since the relationship between SN and particulate mass loading (gravimetric exhaust concentration) is exponential (53), these increases represent very substantial increases in absolute particulate emission levels.

Even smaller changes in fuel hydrogen content can significantly affect smoke emission. Testing of combustion systems on both JP-4 and either JP-5 or Jet A has indicated that smoke levels are substantially lower with JP-4 (54). The slightly higher hydrogen of JP-4 (about 14.5 vs. 13.9 weight % for Jet A) is thought to be primarily responsible for the increase. Figure 9 illustrates one example of this type of result for the case of the CJ005 (J79) engine (55).

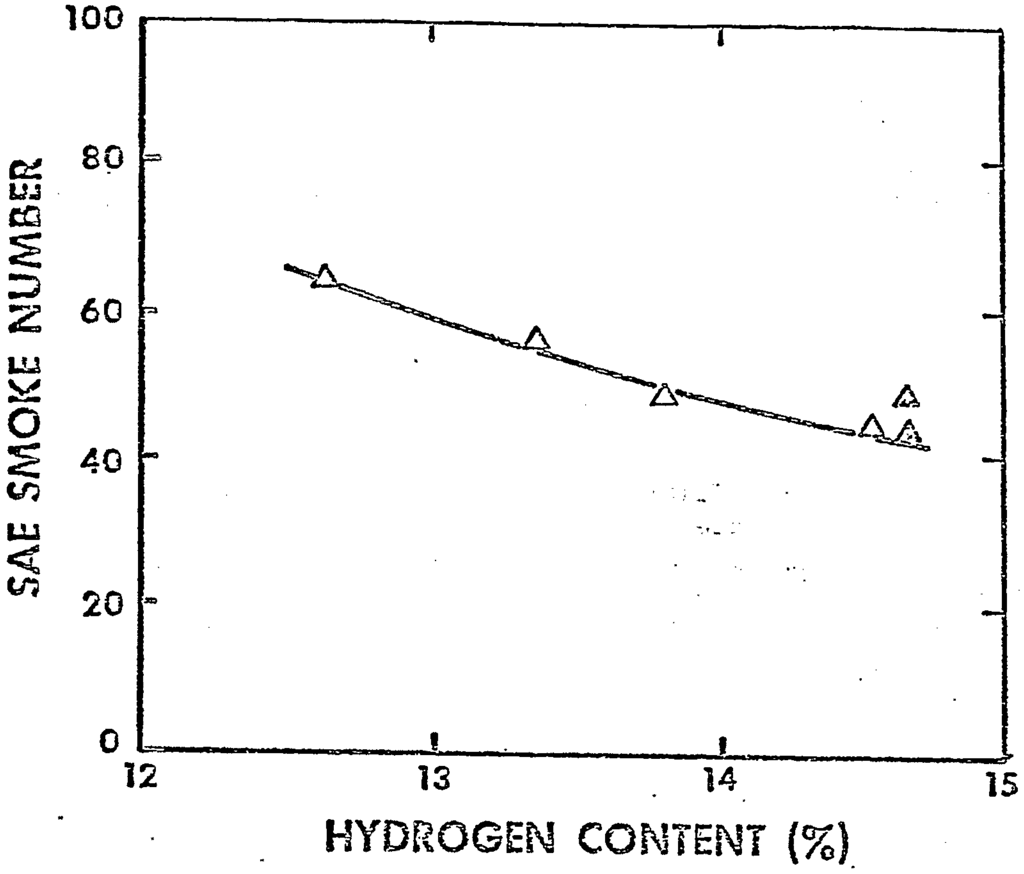


Figure 8: Impact of Reduced Hydrogen Content on Smoke Emission (From Reference 51)

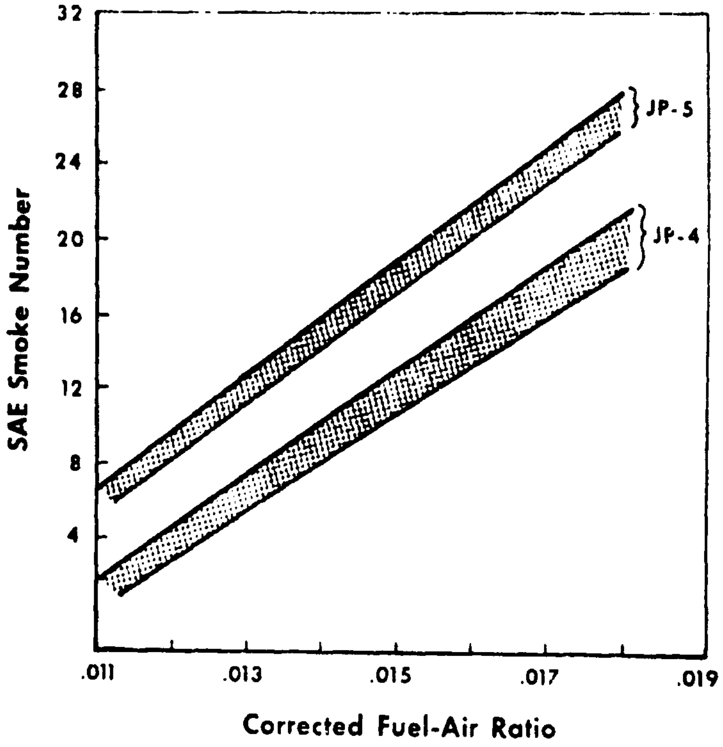


Figure 9: Effect of Fuel Type on Smoke Emission from a CJ805 (J79) Engine with Low-Smoke Combustor (Reference 55)

3. Flame Luminosity Effects

The flame in a gas turbine combustion system radiates energy to the combustor liners which must be cooled with substantial quantities of compressor discharge air (47,51,56-62). Radiation may be considered both luminous and non-luminous. The non-luminous infrared emission is due to CO_2 and H_2O band radiation while the luminous component is due to radiation from carbon particles within the flame. The non-luminous portion of the flame emissivity can be calculated from the equation (56,59):

$$\varepsilon_{n\ell} = 1 - \exp\left(-2.86 \times 10^2 \, P \, (r\ell)^{0.5} \, T_f^{\,-1.5}\right)$$

where: P = combustor pressure $\frac{kN}{m^2}$

r = fuel-air mass ratio

ℓ = radiation path length (m)

T_f = flame temperature (°K)

The conditions which would result in the highest value of $\varepsilon_{n\ell}$ correspond to high power operation of a modern high bypass ratio engine:

P = 30 atm = 3039 $\frac{kN}{m^2}$

r = .05

ℓ = 7.5 cm = .075 m

T_f = 2500°K

Even under these conditions $\varepsilon_{n\ell}$ is only 0.346. Consequently, non-luminous radiation does not approach optically-thick conditions. Increases in luminous emissivity resulting from use of a low hydrogen content fuel can have substantial heat transfer impact.

Many investigators have studied the effect of fuel characteristics on flame luminosity and the resulting effects (51,63-69). Figure 10 illustrates a correlation of much of this data. This figure illustrates the relationship between hydrogen content and combustor liner temperatures for a number of aircraft gas turbine engines. The ordinate in Figure 12 is a non-dimensional temperature parameter (51); $T_L - T_{L0}$ is the difference between liner temperature with a given hydrogen content fuel and that obtained with a standard fuel (in this case JP-4 with 14.5% hydrogen content) and $T_{L0} - T_3$ is the difference between the JP-4 liner temperature and the combustor inlet temperature. The parameter is representative of the fractional increase in liner temperature (over the baseline JP-4 case). Thinking of the liner as a radiative heat flux gage, the parameter is also representative of additional radiative loading.

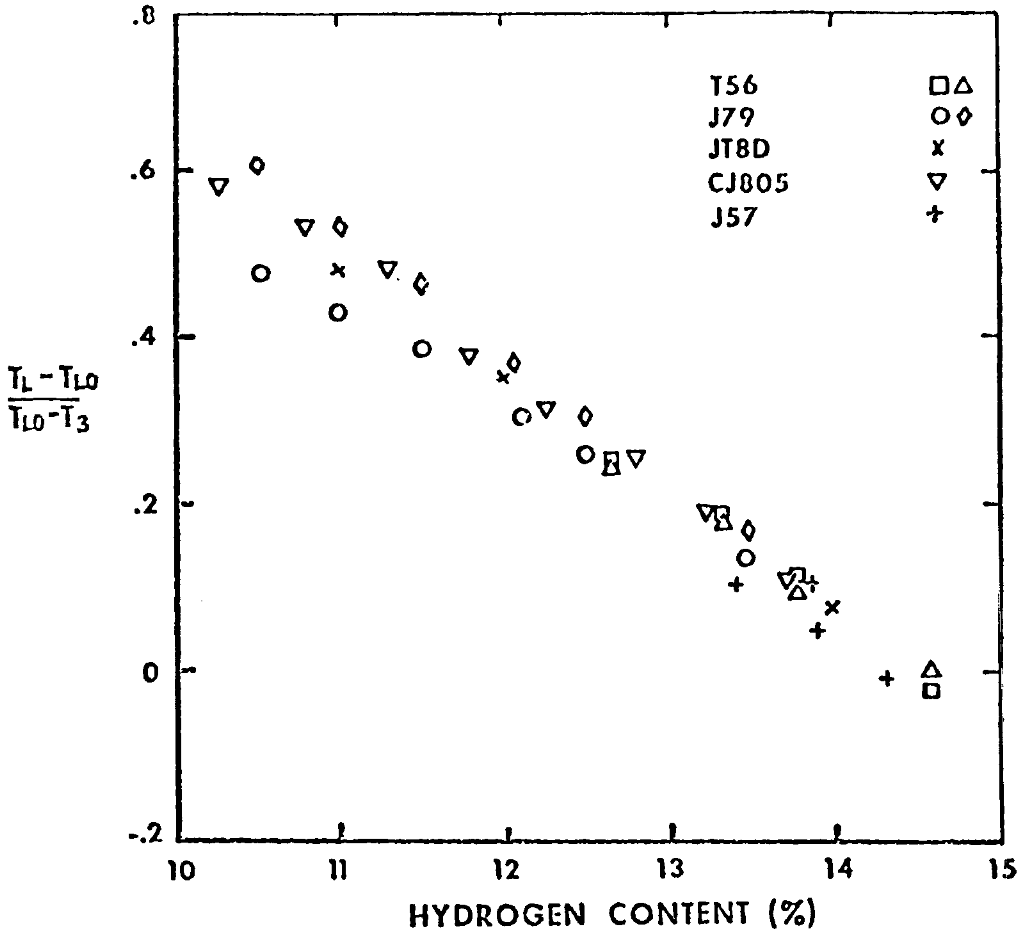


FIGURE 10: Impact of Reduced Hydrogen Content on Combustor Liner Temperature (T_L = combustor liner temperature with test fuel, T_{LO} = combustor liner temperature with 14.5% hydrogen JP-4, and T_3 = combustor inlet temperature. (From Reference 51)

A non-dimensional temperature parameter of 0.25 represents a substantial liner temperature increase. Since $T_{LO}-T_3$ could be about 300°C, the increase in liner temperature over that of the standard fuel would be 75°C. Such changes, especially as they occur at highly stressed combustor locations, can seriously reduce hardware reliability and durability.

A simplified radiation heat transfer analysis of the combustor liner temperature data has produced a relationship between particulate concentration in the primary zone (which increased luminosity) and the fuel content (68). The relationship is of the form:

$$\frac{P_C}{(P_C)_o} = 1 + C_1 \ (\Delta H)^n$$

where: P_C = particulate concentration

$(PC)_o$ = particulate concentration with JP-4

C_1 = constant

$\Delta H = 14.5 - H$: where 14.5 = JP-4 hydrogen content and H is the hydrogen content of the test fuel

$n = 0, 1, 2,$ etc.

The best fit of the data of Figure 12 indicated that $n = 1$.

More detailed evaluations of hydrocarbon type on the enhancement of luminous radiation have been pursued (68). Figure 11 illustrates the influence of single and double ring aromatic compounds on the previously described non-dimensional temperature parameter using results from testing with a T56 single combustor. Different hydrocarbon compounds were added to the fuel to achieve reduction in hydrogen content—napthalene is an unsaturated double ring compound, tetralin is double ring with one saturated and one unsaturated ring, decaline is a saturated double ring compound, and xylene is a single ring unsaturated compound with two methel groups. The figure illustrates that in this instance hydrogen content is a sufficient correlating parameter and hydrocarbon-type influences are secondary.

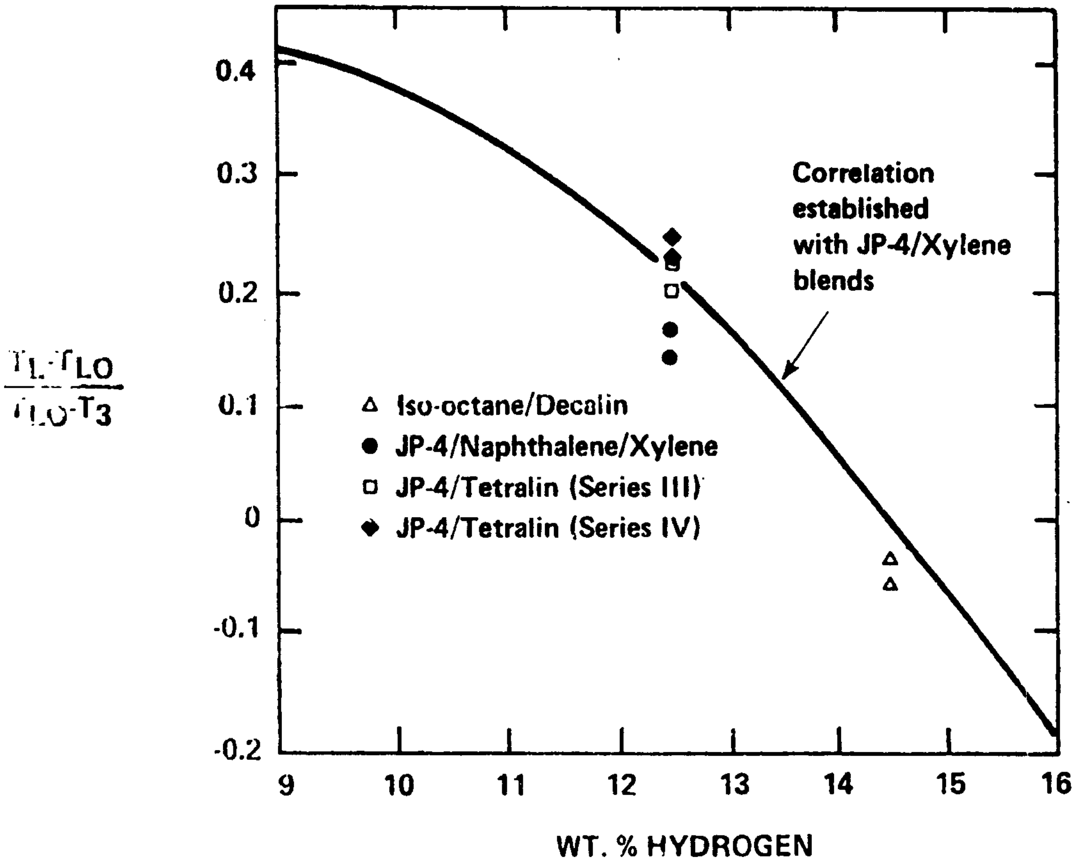


Figure 11: Effect of Low Hydrogen Content Blending Compounds on Correlation (From Reference 68)

B. Fuel Nitrogen Content

1. Fuel Nitrogen → NO_x Chemistry

A number of researchers have studied the fuel nitrogen problem from a fundamental standpoint (70-79). All indications point towards extremely rapid conversion of the fuel nitrogen to a nitrogen-containing intermediate with subsequent rapid oxidation to NO. Some correlations and models have been suggested but it seems certain that only at rich mixture ratio conditions can minimization of NO_x formation be possible.

Equilibrium conditions at rich mixture conditions call for the fuel nitrogen to be converted largely to N_2. Sufficient time for the approach to equilibrium must be allowed; otherwise large quantities of the nitrogen containing intermediates can enter the burnout stage and be converted to NO_x during that process. Consequently, the kinetics of the initial fuel pyrolysis and partial oxidation process must be evaluated.

The key research needs in this area focus on: a) how to accomplish rich combustion without detrimental side effects (smoke, hardware carboning, flame radiation) and b) what are the products of rich combustion which must be accommodated in the second stage combustion process. The time requirements, volumetric loading limitation, inlet temperature influence, and fuel type variations must all be considered in establishment of the rich operating limits. The form of the nitrogen compounds as they exit this first stage (i.e. NH_3, CHN, NO, etc.) as a function of operating conditions will be important to the design of the second stage burnout process. The possibility that some of the fuel nitrogen is present in the soot particulate must also be examined.

Previous work in strongly backmixed systems again focuses on the jet stirred reactor. Bartok et al. (75) established NO_x conversion efficiencies dependence on mixture ratio for methane combustion with addition of NH_3, $(CN)_2$, and CH_3NH_2. Conversion was clearly decreased by operation at greater-than-stoichiometric mixture ratios. Figure 12 illustrates jet-stirred reactor conversion rates for propane fuel doped with 500ppm CH_3NH_2.

2. Effects on Engine Emission

The importance of nitrogen in future fuels arises from its high conversion (30-100%) to NO_x. The extent of this problem in future continuous combustion systems is a complex issue. Most importantly, the levels of nitrogen which might be expected in future fuels have not been defined.

Discussion at the recent NASA hydrocarbon fuels workshop (80) indicated that the impact of fuel nitrogen on the storage and thermal stability of jet fuels may dictate levels which, even if completely converted to NO_x, would be nearly undetectable. This conclusion, however, was drawn in consideration of petroleum-derived fuels and current technology aircraft systems and refining methodology. A more long range look at the jet fuel nitrogen issue, where non-petroleum fuels and improved techniques for coping with stability difficulties are considered, may alter this assessment.

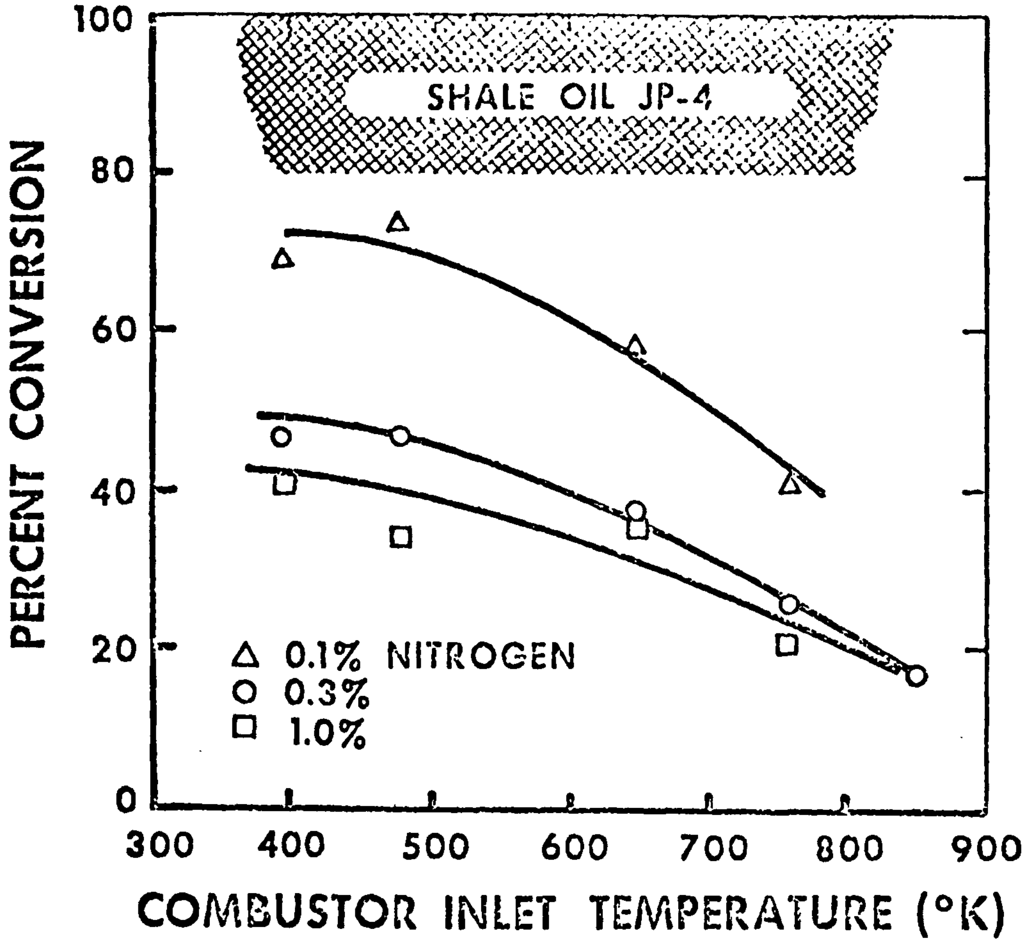


Figure 13: Fuel Bound Nitrogen Conversion to NO_x in an Aircraft Gas Turbine Combustor (From Reference 51)

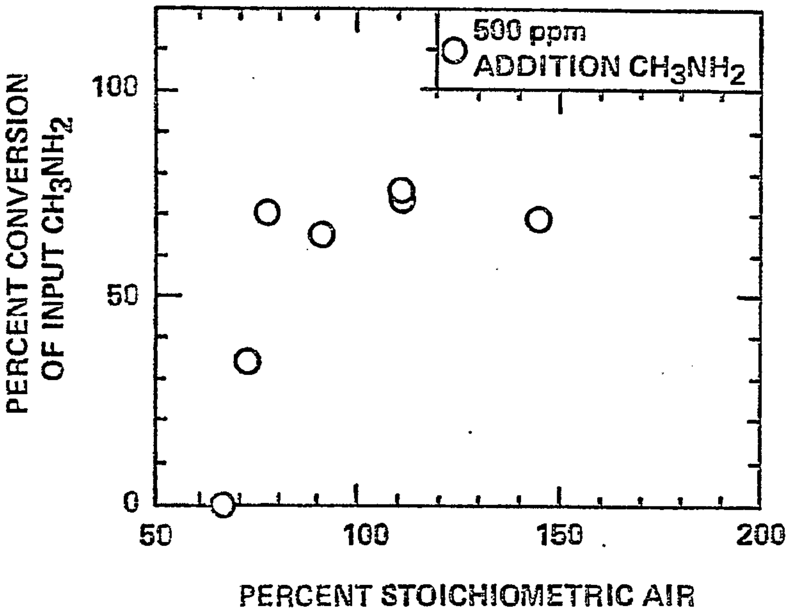


Figure 12: Conversion of CH_3NH_2 to NO_x (From Reference 75)

The effect of increased fuel bound nitrogen in actual engine systems, is evaluated by determining the additional NO_x emission occurring when nitrogen is present in the fuel and calculating the percent of fuel nitrogen conversion to NO_x necessary to cause this increase. Current petroleum jets fuels which have near zero (< 10 ppmw) fuel nitrogen are usually used as the zero fuel nitrogen baseline. Results presented in Figure 13 were acquired using a standard JP-4 fuel doped with pyridine to fuel nitrogen levels of 0.1, 0.3, and 1.0 weight percent (51). A T56 single combustor was utilized in this testing. These results indicate the importance of two variables. First, as combustor inlet temperature is increased, conversion is reduced. Secondly, as fuel nitrogen concentrations are increased, conversion decreases. Other results of gas turbine combustor testing have reached these same conclusions (66,67,81-84).

Another observation to be made with the information presented in Figure 13 is the conversion achieved with nitrogen naturally present in a refined jet fuel from a non-petroleum source. In this case the fuels were derived from Colorado oil shale resources and nitrogen contents of 250-800 ppm resulted. The oil shale jet fuel results are shown on a band in Figure 13 because of difficulties in accurately measuring small NO_x increases.

C. Fuel Stability

In many aircraft applications the fuel is used as a coolant prior to being combusted. Subsonic applications use the fuel to cool engine oil while supersonic-cruise aircraft may also require the fuel to serve as a heat sink for aerodynamic heating effects. As the fuel enters the combustor it flows through hardware (fuel nozzles, fuel pipes, manifolds, etc.) exposed to high temperature due to heating by the compressor discharge air and often radiant heating from the combustion zone. For these reasons the thermal stability is a closely monitored fuel quality.

The combustor designer must recognize this fuel limitation and take appropriate precautions to prevent the fuel from reaching temperatures where thermal breakdown leading to deposition can occur. Designs for low emissions involving fuel staging are especially troublesome in this respect. As the fuel flow to a stage of the combustor is started or stopped the fuel is exposed to a transient heating. After starting the hardware may be at an initial temperature corresponding to the compressor discharge and thus, the fuel is exposed to very high wall temperatures for a brief period. After stopping, the fuel may reach high temperatures as it slowly drains from the system with no supplemental cooling.

Another potential difficulty is the formation of carbon deposits within the combustion system. These would be distinctly different then those within the fuel system which are formed in the absence of oxygen. Unplanned impingement of fuel on combustor walls with the use of airblast fuel injection techniques, can result in substantial carbon deposit buildup. In addition to the difficulties associated with a distorted aerodynamic situation, fragments of deposit can separate from the hardware, pass through the combustor and impinge on the turbine (85).

The introduction of lower hydrogen, higher nitrogen content fuels would further aggravate the design difficulties of coping with the fuel's limitations. The techniques which would be expected to offer improved fuel flexibility (eg. airblast atomization and staged combustion) may experience especially difficult problems because of liquid fuel contact with metal surfaces and intermittant fuel nozzle usage.

D. Other Fuel Factors

Volatility affects the rate at which liquid fuel introduced into the combustor can vaporize. Since important heat release processes do not occur until gas phase reactions take place, reduction of volatility shortens the time for chemical reaction within the combustion system. In the aircraft engine this can result in difficulty in ground or altitude ignition capability, reduced combustor stability, increased emissions of carbon monoxide (CO) and hydrocarbons (HC), and the associated loss in combustion efficiency. Moreover, carbon particle formation is aided by the formation and maintenance of fuel-rich pockets in the hot combustion zone (86). Low volatility allows rich pockets to persist because of the reduced vaporization rate. Again, increased particulates can cause additional radiative loading to combustor liners and increased smoke emission between JP-4 and JP-5. Some of the differences between JP-4 and JP-5 smoke levels (Figure 11) can be attributed to the volatility effect.

The desired formation of a finely dispersed spray of small fuel droplets is adversely affected by viscosity. Consequently, the shortened time for gas phase combustion reactions and prolonging of fuel-rich pockets experienced with low volatility can also occur with increased viscosity. The ignition, stability, emissions, and smoke problems previously mentioned also increase for higher viscosity fuels.

Both sulfur and trace metals are at very low concentrations in current jet fuels. Sulfur is typically less than 0.1% because the petroleum fraction used for jet fuel production is nearly void of sulfur-containing compounds. Although syncrudes from coal or oil shale may contain higher sulfur levels, it is not likely that the current specification limit of 0.4% would be exceeded with the processed jet fuel. The nature of modern turbine blade design and the operating temperatures in this component require that the trace metals be removed. Because of the way in which future jet fuels are expected to be produced, trace metals are also expected to continue to be present at low concentrations (less than 1 ppmw). Should higher levels appear possible, the necessity to preserve the high fuel efficiency benefits of the advanced technology turbine blade would justify additional expense for removal.

IV. CHANGES FOR FUEL FLEXIBILITY

In consideration of future R&D requirements, this Section presents the types of designs which might be expected to afford some fuel flexibility are described.

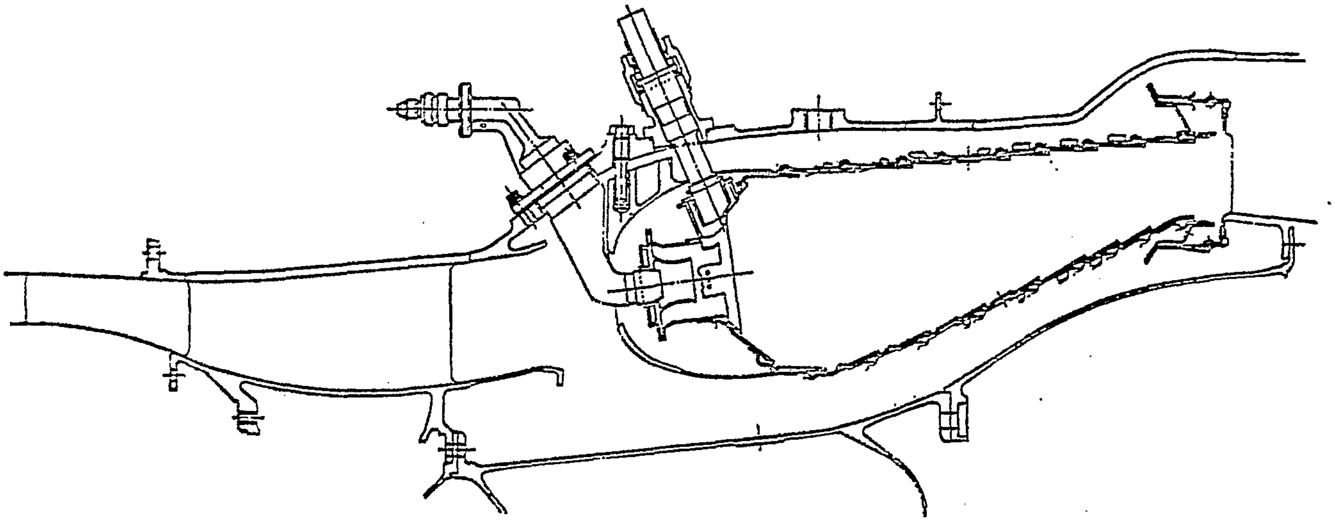
1. Premixing/Prevaporization/Lean Operation

Since carbon particulate formation occurs at fuel-air ratios above a limit determined by the fuel composition, it is evident that the primary approach towards eliminating luminous radiation and smoke problems is to maintain fuel-air ratios below the incipient carbon formation limit at all points within the combustor. To assure this situation the maximum degree of premixing, prevaporization, and lean operation should be pursued. The ability to incorporate these design characteristics, however, is seriously limited by the difficulties to be described below.

The most recent current designs incorporate some degree of premixing and lean operation to minimize smoke emission while using fuels within existing specifications. The General Electric CF-6 combustor illustrated in Figure 14 utilizes airblast atomization and a lean primary zone. Testing of the CF-6 combustor has produced results which indicate combustor liner temperature dependencies on fuel hydrogen content significantly below that of older designs (87). Figure 15 compares the non-dimensional temperature parameter for the CF-6 with that of the older designs established as Figure 12. Interpreting the non-dimensional temperature parameter in terms of a heat flux parameter, it is clear that the fractional increase in combustor thermal loading resulting from luminous radiation is far less for the CF-6 combustor.

Low NO_x emissions designs tested in the NASA Experimental Clean Combustor Program have a leaner, more premixed design. These advanced combustors make use of a staged design as illustrated in Figure 16. The first stage, being the only one fueled at idle, is designed forpeak idle combustion efficiency. The second stage is only utilized at higher power conditions. This main combustion zone is designed with the primary motivation of NO_x control and operates fuel lean. It has been found that some of these designs indicate nearly no sensitivity to fuel type; the behavior of such systems as expressed in the manner of Figure 15 would be a horizontal line (87). That is, all fuel air ratios in the combustion zone must have been below the incipient sooting limit.

It should be noted that not all evidence points to greater fuel flexibility for modern engines. During the recent NASA Hydrocarbon Fuels Technology Workshop, combustor liner temperature results from the testing of some of the ECCP advanced combustors was thought to imply an equal sensitivity to the older designs (80). It was generally agreed, however, that the direction in which the ECCP combustor designs proceded to satisfy performance requirements and reduce emissions is favorable to promoting fuel flexibility.



PRODUCTION CF6-50 ENGINE COMBUSTOR

Figure 14: CF6-50 Standard Combustor (From Reference 87)

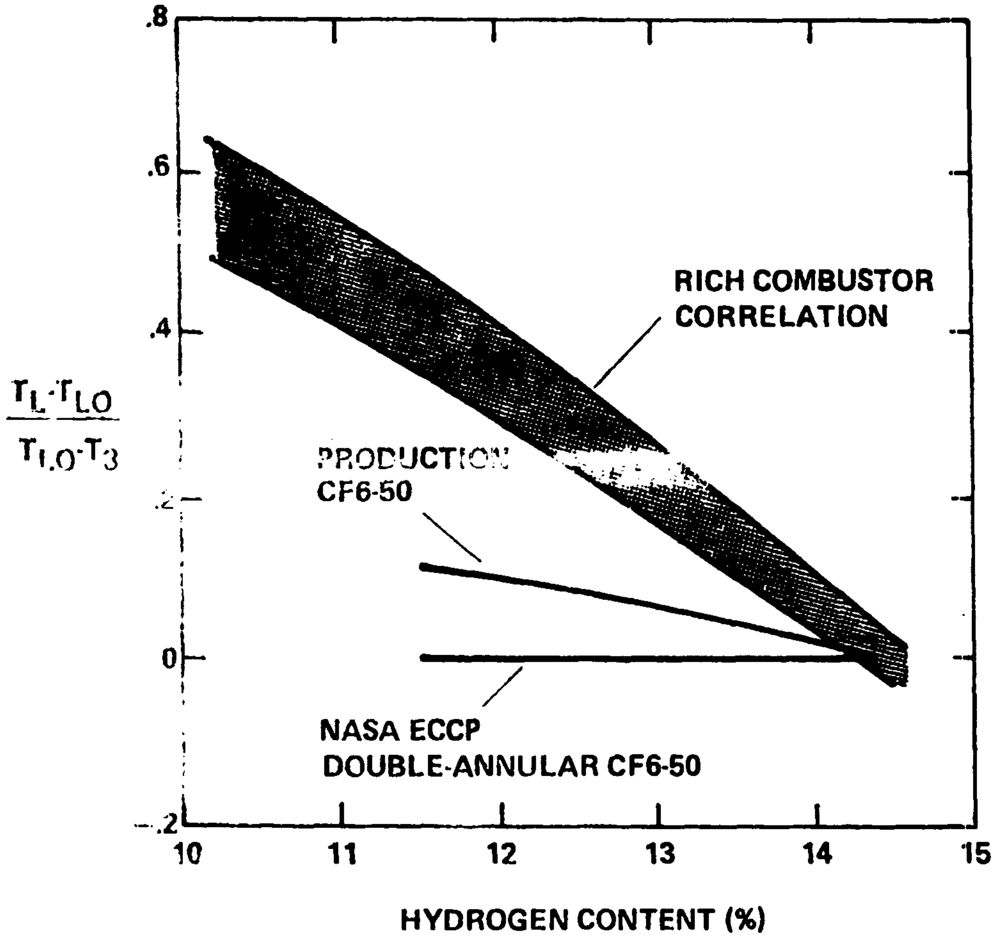
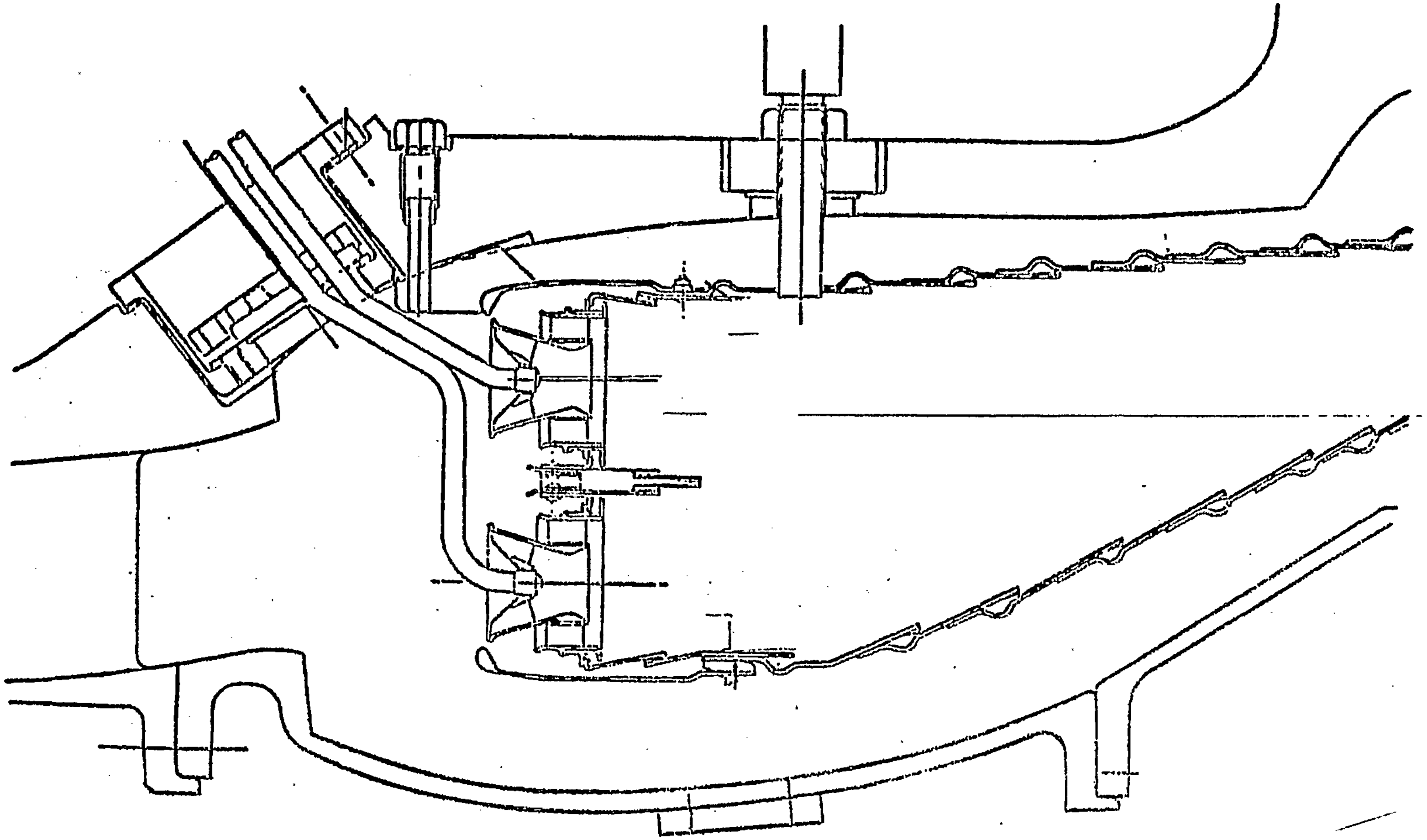


Figure 15: Comparison of Modern and Advanced Designs with Rich Combustor Correlation (CF6-50 and NASA ECCP Data From Reference 87)

Figure 16: GE Double Annular Combustor Developed During NASA ECCP Program (Reference 87)



The designer's ability to incorporate premixing/prevaporization techniques into his combustor is seriously limited by preignition and flashback limitations and by combustor geometry constraints. At the high combustor inlet temperatures and pressures associated with takeoff climbout or cruise operations, the ignition delay time of the fuel air mixture may be less than 10 ms. Should this residence time be achieved prior to the mixing entering the burning zone, ignition will occur with resultant destruction of the combustor hardware. If droplet size is too large the prevaporization passage may be too short to accomplish sufficient vaporization. Recognizing the need for future premixing/prevaporization systems a number of efforts have begun to collect fundamental information of methods of best achieving this condition in practical systems (88,89).

2. Combustor Liner Cooling

A second, or perhaps additional, approach to avoiding hardware distress resulting from increased flame luminosity is the use of advanced combustor liner cooling techniques. Three concepts are to be reviewed here: impingement/film cooling, transpiration cooling, and thermal barrier coatings. Figure 17 illustrates characteristics of each of these techniques.

The impingement/film cooling technique is well suited for applications involving high radiative flux and minimum availability of cooling air. Small jets of air impinge on the hot side of the combustor liner providing very effective heat transfer. When combined with the additional film cooling feature (see Figure 3), impingement cooling provides for excellent thermal protection of a high temperature liner. Its disadvantages, however, are similar to those of the film/convection liner--heavier construction, manufacturing complexity and repairability difficulties.

Transpiration cooling is the most advanced cooling scheme available and is particularly well-suited for future high temperature applications. Cooling air flows through a porous liner material, uniformly removing heat from the liners while providing an excellent thermal barrier to high combustion gas temperature. Both porous (regimesh and porolloy) and fabricated porous transpiring materials (Lamilloy*) have been examined experimentally. Fabricated porous materials tend to alleviate plugging and contamination problems, inherent disadvantages of the more conventional porous materials. As can be seen in Figure 17, transpiration cooling offers better temperature control and uniformity than any other cooling technique.

Beyond these techniques are other approaches involving coatings and thermal barriers. Recent efforts at NASA Lewis Research Center have illustrated that thermal barriers can provide significant relief from high radiative loads allowing acceptable metal temperatures in conventional combustion designs when burning fuels with low hydrogen content (90). The thermal barrier consisted of a 0.01 cm bond coat of nickel-chromium-aluminum-yttrium alloy covered with a 0.025 cm ceramic layer of 12% yttria stabilized zirconia. Combustor liner metal temperature decreases of over 200°C were indicated when using a high aromatic fuel.

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* Developed by Detroit Diesel Allison, Div. of GMC, Patent Number 3,584,972, titled "Laminated Porous Material," 15 June 1971.

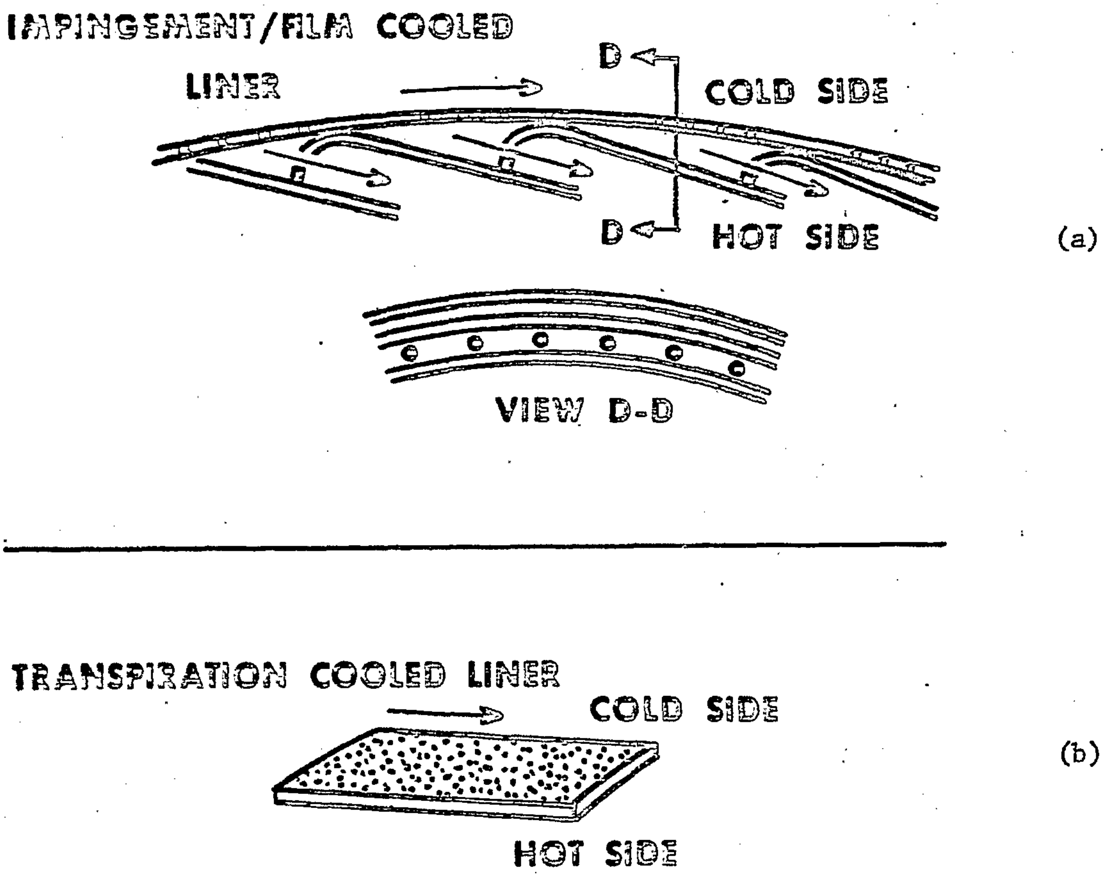


Figure 19: Advanced Combustor Liner Cooling Techniques a) Impingement/Film Cooling, and b) Transpiration Cooling.

3. Minimizing Smoke Emission

The most attractive means of controlling smoke emission is to maintain fuel-air ratio conditions throughout the combustor at values below the incipient carbon formation limit. However, because of the practical problems presented by premixing, prevaporization, and lean combustion, this may not be possible. In such a case the previously discussed liner cooling techniques will be of value in handling the increased amounts of luminous radiation.

Carbon particulates which are formed will have to be oxidized within the secondary zone. Close control of mixture ratio, temperature and residence time within this zone will be necessary to achieve maximum consumption. Radcliffe and Appleton (91) have determined that optimum consumption of particulates occurs at $\phi = 0.75$. Their particle surface consumption rates of 1-20 μm/sec. indicate that particles whose initial diameter is less than 0.04 μm will be consumed in a typical residence time of five ms. Even with optimum conditions, however, it may not be possible to consume sufficient amounts of soot to provide acceptable exhaust levels, especially if significant agglomeration has occurred to form particles larger than 400 Å.

4. Fuel Nitrogen Conversion

The primary approaches to minimizing fuel nitrogen conversion to NO_x involve rich combustion to react fuel nitrogen to N_2 followed by lean burnout of the rich zone products. The necessity for the rich combustion zone creates substantial difficulty in the task of preventing carbon particulate formation. In brief, this limits the "window" of premixed prevaporized conditions which the designer must satisfy and creates the necessity for a sequentially staged design (rather than spacially or parallel staged design as in the NASA ECCP combustors). Difficulties associated with the conflicting approaches to soot minimization and fuel nitrogen → NO_x control coupled with thermal stability requirements will certainly contribute towards a preference to remove nitrogen from future aviation fuels.

5. Other Fuel Characteristics

Fuel thermal stability, volatility, viscosity, and sulfur and trace metal content would have significant impacts. As previously discussed, thermal stability might become a more significant problem in staged designs where fuel introduction systems are started and shut down frequently, thus undergoing substantial thermal transients. Cautious design of fuel system components and control of fuel quality will be required to overcome this difficulty.

Reduced volatility and increased viscosity would impact ground and altitude ignition capabilities. It must be emphasized that the system must be designed for and qualified at the most stringent operating parameters (in this case lowest temperature) and future fuels might have very difficult properties at such conditions.

V. R&D NEEDS

The purpose of this section is the identification of basic combustion phenomena requiring further study along with indications of priority for accomplishing this work. These thoughts must be related to the foregoing discussion of alternate fuels problems in gas turbine combustion systems. This will be accomplished by a matrix which depicts the relationship between combustion system performance and fuel characteristics. The matrix provides a means of identifying major areas requiring attention. A second matrix relates the key combustion processes requiring study to the problem areas identified.

Combustion system influences which must be considered in this analysis are:

- ignition
- combustion stability
- combustor liner temperature and deposits
- combustion efficiency
- gaseous emissions
- smoke emission
- trace emission
- flashback and preignition

With the exception of the last two items, these topics have already been adequately discussed. Trace emission relates to the potential emission of material which is not governed by current regulations. For example, the more aromatic nature of future fuels might cause increased emission of polynuclear organic material either in the gaseous state or adsorbed on emitted particulates. Another possibility would be trace metal emissions associated with increased amounts of these materials in fuels. Flashback and preignition becomes an important influence with future combustion systems because of the need to premix and prevaporize to provide stable, lean combustion to minimize soot and NO_x formation. As these combustors are developed, the influences of the fuel characteristics on flashback and preignition must be considered.

Figure 18 relates these combustion system influences to the fuel characteristics discussed in previous sections: fuel hydrogen content and changes in hydrocarbon composition, nitrogen content, fuel thermal stability, volatility, viscosity, trace metal content, and sulfur content. Problems known to exist because of future changes in each fuel characteristic are designated with a P. Potential problems are indicated with a p. The seriousness of the problem is indicated numerically with 1 being a minor problem and 3 being a major problem. The matrix illustrates that attention should be focused on:

a. Fuel hydrogen content effects on combustor durability and smoke emission.

b. Fuel nitrogen conversion to NO_x. Note that this conclusion applies directly to non-aircraft turbine only as future jet fuel nitrogen levels are very uncertain (see Section IV).

Figure 18

Relationships Between Fuel Property Changes and Combustion System Effects

Combustion System Effect Fuel Characteristic	Ignition	Combustion Stability	Combustor Liner Temperature and Deposits	Gaseous Emissions	Smoke Emission	Trace Emission	Flashback and Preignition
Fuel H Content and Changes in Hydrocarbon Composition			P3		P3	p	P2
Fuel N Content				P3*			
Thermal Stability			P2				
Volatility	P2	P1		P2	P2		
Viscosity	P2	P1		P2	P2		
Trace Metals						p	
Sulfur Content						p	

P: Known problem

p: Potential problem

1 → 3: Extent of problem 1 = minor, 3 = major

* Extent of problem not certain for aircraft turbines

c. Fuel hydrogen content (hydrocarbon composition) influences on preignition/flashback in combustion systems.

d. Thermal stability influences on deposits, especially for future prevaporization/premixing designs.

e. Volatility effects on ignition, gaseous emission, and smoke.

f. Viscosity effects on ignition, gaseous emissions, and smoke.

g. Hydrogen content, trace metal, and sulfur effects on trace emissions.

While this prioritization of gas turbine combustion problems is interesting in itself, it only provides guidance for formulation of the appropriate fundamental combustion program. Figure 19 provides a schematic representation of the combustion model being developed in this program. The framework of the model provides a structure for thinking of the basic combustion phenomena requiring improved understanding, as well as for determining requirements which can lead to the ability to analytically predict fuel effects on combustion systems. Fuel related elements of the model are those appearing in the upper left portion of the schematic. A final key element requiring attention is flame radiation and the ability to predict variations in it with fuel type.

These elements have been presented along with the key system problems expected (as previously discussed) in the final matrix of Figure 20. Here the priority problems are related to items which we can study and from which our program can be formulated. Note that the potential for studying the deposit problems associated with low thermal stability using a combustion model is very low; new experimental procedures for evaluation of thermal stability difficulties must be pursued. Further, while the H_2 and CO oxidation chemistry will play a vital role in the combustion chemistry, additional information on this process is not necessary to allow prediction of fuel effects.

It is apparent that the following ordering of priority should be respected in selection of tasks for future program years.

a. Soot Formation

b. Fuel Pyrolysis

c. Soot Oxidation

d. Flame Radiation

e. Bound Nitrogen → NO_x Conversion

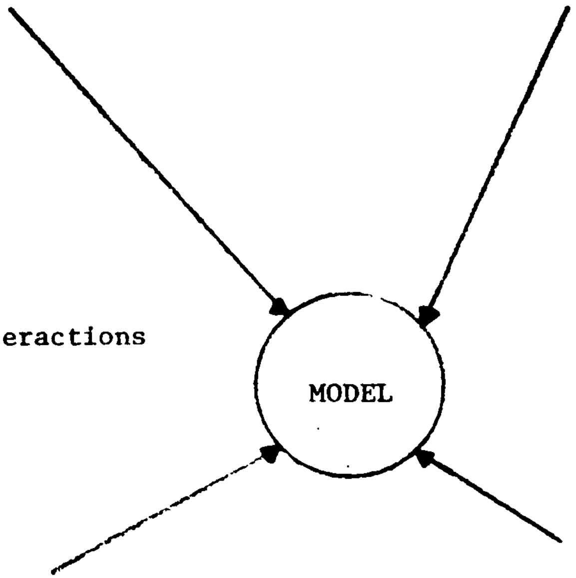
f. Aerodynamic Chemical Interactions

g. Fuel Vaporization and Spray Dynamics

It should be noted that these topic areas are not very sharply defined. For example, soot formation occurs during fuel pyrolysis and one topic could not be totally excluded from study of the other. Further, the difference in the priority of the first five items is very small. Bound nitrogen conversion should be given urgent priority even though it is fifth on the list.

Figure 19

Schematic Representation of a Combustor Model
(Elements influencing ability to predict fuel effects designated by *)



CHEMICAL AND FUEL RELATED ELEMENTS

- * Fuel Vaporization and Spray Dynamics
- * Fuel Pyrolysis
- * Soot Formation
- * Bound N → NO_x Conversion
- * H_2 and CO Oxidation
- * Soot Oxidation
- * Aerodynamic/Chemical Interactions

THERMODYNAMIC AND HEAT TRANSFER ELEMENTS

- Conduction
- Convection
- * Radiation
- Turbulence Effects
- Energy Balance and Temperature Determination

GAS PHASE ELEMENTS

- Mass and Species Conservation
- Momentum Conservation
- Energy Conservation
- Species Diffusion
- Turbulence Model

SOLUTION SCHEME

- Simplification of Equations
- Solution Procedure
- Criteria for Solution Acceptance

Figure 20

Relation of Key System Problems to Combustion Phenomena

System Problems / Combustion Phenomena	a. Fuel H Effect on Combustor T and Smoke	b. Fuel N Effect on NO_x	c. Fuel H Effect on Flashback/Preignition	d. Thermal Stability Effect on Deposits	e. Volatility Effects on Ignition and Emissions	f. Viscosity Effects on Ignition and Emissions	g. Effects on Trace Emission
1. Fuel Vaporization and Spray Dynamics	M				S	S	*
2. Fuel Pyrolysis	S	S	S	M			*
3. Soot Formation	S						*
4. Bound N → NO_x Conversion		S					
5. H_2 and CO Oxidation							
6. Soot Oxidation	S						*
7. Aerodynamic/Chemical Interaction	*	*	*		*	*	*
8. Flame Radiation	S						

S - Substantial influence

M - Minor influence

* - Expected influence but not quantified.

VI. CURRENT EXPERIMENTAL PLAN

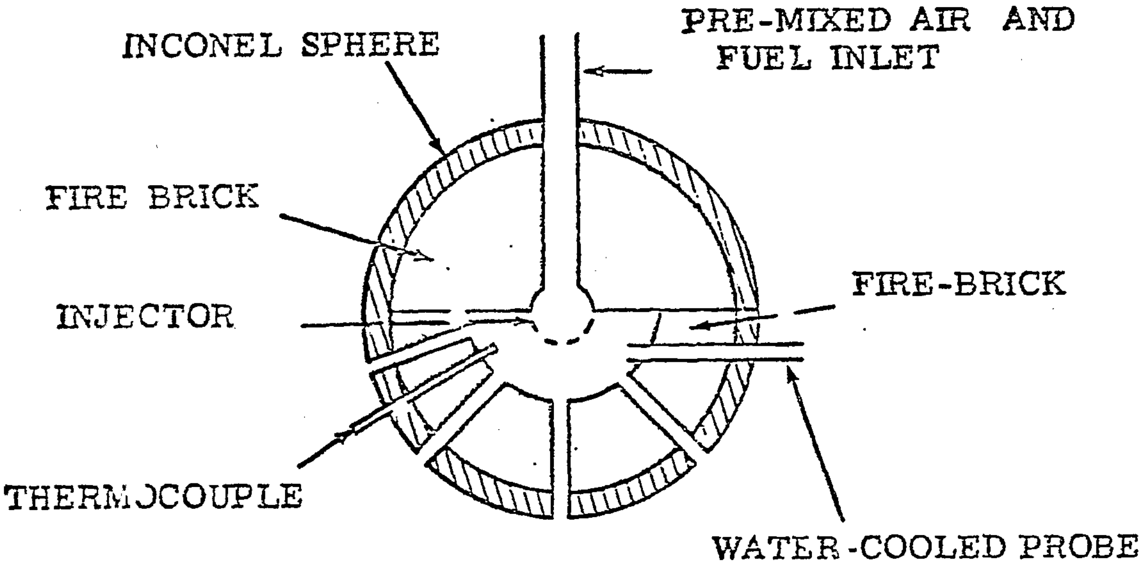
The current experimental program focuses on study on the soot formation process using the jet-stirred combustor. This device is a modification of the Longwell-Weiss reactor (92) with hemispherical geometry. This choice has been used extensively in fluid mechanic and combustion modeling because combustion rates are limited by chemical kinetics as opposed to transport effects. The reactor (Figure 21) consists of an outer shell of fire brick shaped as two halves of a sphere five inches in diameter. The upper hemisphere is solid with the exception of the hole through which the reactants are brought to the injector. The lower hemisphere is hollowed out to a reaction zone of 1.5 inch diameter and has twenty-five holes of 0.125 inch diameter through which the burned mixture exhausts. New reactors are being fabricated which will allow for different diameter reaction zones (1 and 2 inches as well as 1.5 inch) and to evaluate reactor heat loss effects.

Fuel and air are metered separately through calibrated rotameters, preheated to the desired inlet temperature and then mixed before entering the combustor. Air and fuel heating to temperatures of 350°C (and fuel prevaporization in the case of liquids) is accomplished in an "aluminum block heater". Separate coils for fuel and air are embedded in the block which is wrapped with electrical resistance heaters. In the case of liquid fuels, a small flow of N_2 is maintained through the fuel coil to provide smooth vaporization and uniform flow. The temperature of the fuel/air stream is determined immediately before injection. This measurement is input to a digital controller which provides power to the block heater to maintain injector inlet temperature within ± 3°C of the set point. The fuel-air mixture enters the reaction zone through an Inconel injector which is a hemisphere into which are drilled forty radial holes of 0.020 inch diameter. The above mentioned new JSC design will allow for rapid changing of injectors in case of burnout or to determine the effects of injector head design. The reactants enter the reaction zone as small sonic jets which stir the reactor contents and produce a mixture of essentially uniform temperature and composition in a characteristic time which is short compared with the average residence time. Combustion experiments can be conducted at atmospheric pressure with a range of residence times from 1-1/2 to 4 milliseconds. The capabilities of this apparatus may be extended to include operation above atmospheric pressure as part of the current DOE effort.

A new system for gas and particulate sampling has been developed. Special care has been taken to prevent condensation of water or unburned hydrocarbons within the sample lines, as high concentrations of these constituents are expected at mixture ratios of interest in this study. The sampling probe is hot-water cooled and sample transfer is accomplished using electrically heated sample lines. All pumping and valving is accomplished within an oven maintained at 150°C. Valves have been selected which are rated for operation at temperatures up to at least 175°C and design characteristics are such that lubricated valve components are sealed from the gas path. The pump selected is a high temperature metal bellows type (Model MD-158 HT) driven by a 1/4 horsepower motor external to the oven.

Figure 21

Schematic of the Jet Stirred Combustor



Gas sampling is accomplished with conventional process instrumentation. Gases leaving the oven are transferred hot (150°C) to a Beckman Model 402 Analyzer for hydrocarbon measurement. Another sample gas stream is chilled to eliminate condensable water and hydrocarbons prior to introduction into NDIR analyzers for CO and CO_2, and an amperometric instrument for O_2. Particulate sampling will be accomplished using a 40 mm glass fiber type filter (Gelman type AE). Pre- and post-weighing (after appropriate drying) will be utilized and sufficient collection in times of less than 10 minutes is expected.

Ethylene has been used as the base fuel for this program. Liquid fuels to be studied are:

n-octene
cyclo-octane
hexane
cyclo-hexane
n-octane
iso-octane
toluene
ortho-xylene
meta-xylene
para-xylene
cumene
tetralin
decalin
1-methyl napthalene
dicyclopentadiene

Early experiments will involve C_2H_4 as the fuel and will focus on determining the effects of reactor loading and inlet temperature on the incipient soot limit and soot formation rate. Gaseous specie concentration will also be determined to evaluate the changes in hydrocarbon, CO, and CO_2 concentration as the soot limit is reached and exceeded.

Similar experiments will follow using the liquid fuels. The objective of these studies will be to evaluate the effect of hydrocarbon structure on sooting characteristics under intensely backmixed conditions. All of this testing will have been conducted using pure fuels. Subsequently, fuel blends will be studied. The relationship between fuel hydrogen content and soot emission will be established. Finally, practical fuel blends (a jet fuel, diesel fuel, and unleaded gasoline) and actual synfuels (coal or oil shale derived) will be tested. The objective of these last tests will be to examine the similarity between results obtained with blends of pure fuels and those of practical fuel mixtures.

REFERENCES

1. Goen, R. L., Clark, C. F., and Moore, M. A., "Synthetic Petroleum for Department of Defense Use," AFAPL-TR-74-115, November 1973.

2. Shaw, H., Kalfadelis, C. D., and Jahnig, C. E., "Evaluation of Methods to Produce Aviation Turbine Fuels from Synthetic Crude Oils, Phase I," AFAPL-TR-75-10, Volume I, March 1975.

3. Bartick, H., Junchal, K., Switzer, D., Bowen, R., and Edwards, R., "The Production and Refining of Crude Shale Oil into Military Fuels." Final Report for Contract N00014-75-C-0055, Office of Naval Research, Arlington, VA, August 1975.

4. Jaarsma, F., "Impact of Future Fuels on Military Aero Engines," AGARD Annual Meeting, 1974.

5. Antoine, A. C., and Gallagher, J. P., "Synthesis and Analysis of Jet Fuels from Shale Oil and Coal Syncrudes," NASA TM X-73399, presented at 82nd National AIChE Meeting, Atlantic City, N. J., August 1976.

6. Longwell, J. P., "Synthetic Fuels and Combustion," Sixteenth International Symposium on Combustion, The Combustion Institute, Pittsburgh, PA, August 1976.

7. Pinkel, I. I., "Future Fuels for Aviation," AGARD Advisory Report No. 93, January 1976.

8. Nestor, L. J., "Investigation of Turbine Fuel Flammability Within Aircraft Fuel Tanks," FAA Report DS-67-7, July 1967.

9. Military Specification MIL-T-5624K, Turbine Fuel, Aviation, Grades JP-4 and JP-5.

10. Standard Specification for Aviation Turbine Fuels, D1655, American Society for Testing and Materials.

11. Maggitti, L., "Interim Progress Report on Development of Alternate Sources of JP-5 Fuel," Naval Air Propulsion Test Center Report, August, 1974.

12. Blazowski, W. S., Fahrenbruck, F. S., and Tackett, L. P., "Combustion Characteristics of Oil Shale Derived Jet Fuels." Paper 75-13 presented at the 1975 WSS/CI Fall Technical Meeting, Palo Alto, California, October 20-21, 1975.

13. Solash, J., Nowack, C. J., and Delfosse, R. J., "Evaluation of a JP-5 Type Fuel Derived from Oil Shale," NAPTC-PE-82, May 1976.

14. Kalfadelis, C. D., "Evaluation of Methods to Produce Aviation Turbine Fuels from Synthetic Crude Oils, Phase 2," AFAPL-TR-75-10, Volume II, May 1976.

15. Nowack, C. J., Solash, J., and Delfosse, R. J., "Evaluation of Coal-Derived JP-5 Fuels," CEP Technical Manual, Volume 3, 1977, pp. 122-126.

16. Moses, C., and Naegeli, D., "Investigation Into the Effects of Extending JP-5 Fuel Specifications on Combustor Performance," Southwest Research Institute report, to be published.

17. Environmental Protection Agency, "Control of Air Pollution from Aircraft and Aircraft Engines," Federal Register, Vol. 38, No. 136, July 17, 1973.

18. Blazowski, W. S., and Henderson, R. E., "Aircraft Exhaust Pollution and its Effect on the U. S. Air Force," AFAPL-TR-74-64, Air Force Aero Propulsion Laboratory, Wright-Patterson AFB, Ohio. August 1974.

19. Roberts, R., Peduzzi, A., and Niedzwiecki, R. W., "Low Pollution Combustor Designs for CTOL Engines--Results of Experimental Clean Combustor Program," AIAA Paper No. 76-762, July 1976.

20. Gleason, C. C., Niedzwiecki, R. W., "Results of the NASA/General Electric Experimental Clean Combustor Program," AIAA Paper No. 76-763, July 1976.

21. Roberts, R., Fiorentino, A. J., and Diehl, L., "The Pollution Reduction Technology Program for Can-Annular Combustor Engines--Description and Results," AIAA Paper No. 76-761, July 1976.

22. Blazowski, W. S., Walsh, D. E., and Mach, K. D., "Operating and Ambient Condition Influences on Aircraft Gas Turbine NO_x Emissions," J. Aircraft Vol. 12, No. 2, pp. 110-115, February, 1975.

23. Faitani, J. J., "Smoke Reduction in Jet Engines Through Burner Design," SAE Paper 680348, April 1968.

24. Durrant, T., Fiorello, S. C., Faitani, J. J., Hochheiser, S., and Lozano, E. R., Combustor Design Changes Reduce Smoke from Gas Turbine Engines, SAE Journal, Vol. 77, No. 6, June 1969, pp. 61-64.

25. Taylor, W. G., Davis, F. F., Jr., DeCorso, S. M., Hussey, C. E., and Ambrose, M. J., "Reducing Smoke from Gas Turbines," Mechanical Engineering, July 1968, pp. 29-35.

26. Hilt, M. B., Fenimore, C. P., and Johnson, R. H., "Hydrocarbon Combustion Smoke and its Elimination from Heavy Duty Gas Turbines," ASME Paper 70-PWR-14, September 1970.

27. Nelson, A. W., "Development of a Reduced Smoke Combustor for the JT3D Engine," SAE Paper 740484, April 1974.

28. Bahr, D. W., Smith, J. R., and Kenworthy, M. J., "Development of Low Smoke Emission Combustors for Large Aircraft Turbine Engines, " AIAA Paper No. 69-493, 1969.

29. Shabod, L. M., and Smirnov, G. A., "Aircraft Engines as a Source of Carcinogenic Pollution of the Environment (Benzo-a-pyrene Studies)," Atmospheric Environment, Vol. 6, pp. 153-164, 1972.

30. Street, J. C., and Thomas, A., "Soot Formation in Premixed Flames," Fuel, Vol. 34, pp. 4-36, 1955.

31. Daniels, P. H., "Carbon Formation in Premixed Flames," Combustion and Flame, Vol. 4, pp. 45-49, 1960.

32. Tesner, P. A., "Formation of Dispersed Carbon by Thermal Decomposition of Hydrocarbons," 7th Symposium on Combustion, 1959.

33. Chakraborty, B. B., and Long, R., "The Formation of Soot and Polycyclic Aromatic Hydrocarbons in Diffusion Flames III; Effect of Additions of Oxygen to Ethylene and Ethane Respectively as Fuels," Combustion and Flame, Vol. 12, pp. 469-476, 1968.

34. Homann, K. H., "Carbon Formation in Premixed Flames," Combustion and Flame, Vol. 11, pp. 265-287, 1967.

35. Gill, D. W., "Review No. 182 - Luminosity and Soot Formation in Hydrocarbon Flames," BCURA Monthly Bulletin, Vol. XXII, No. 12, November-December 1958, pp. 487-506.

36. Clarke, A. E., Hunter, T. G., and Garner, F. H., "The Tendency to Smoke of Organic Substances on Burning," J. Inst. Pet., Vol. 32, pp. 627-642.

37. MacFarlene, J. J., Holderness, F. H., and Whiteher, F. S. E., "Soot Formation Rates in Premixed C_5 and C_6 Hydrocarbon-Air Flames at Pressure Up to 20 Atmospheres," Combustion and Flame, Vol. 8, pp. 215-229, 1964.

38. Schalla, R. L., and Hibbard, R. R., "Smoke and Coke Formation in the Combustion of Hydrocarbon-Air Mixtures," Chapter IX in "Basic Considerations in the Combustion of Hydrocarbon Fuels with Air," NACA Report 1300, 1957, pp. 242-255.

39. Fennimore, C. P., Jones, G. W., and Moore, G. E., "Carbon Formation in Quenched Flat Flames at 1600°K," 6th Symposium (International) on Combustion, pp. 242-246, 1956.

40. Stehling, F. C., Frazee, J. D., and Anderson, R. C., "Carbon Formation from Acetylene," 6th Symposium (International) on Combustion, pp. 247-254, 1956.

41. D'Alessio, A., DiLorenzo, A., Sarofim, A. F., Beretta, F., Masi, J., and Venitozzi, C., "Soot Formation in CH_4-O_2 Flames," 15th Symposium (International) on Combustion, pp. 1427-1438, 1974.

42. Palmer, H. B., and Cullis, C. F., "The Formation of Carbon from Gases," Chapter 5 in Chemistry and Physics of Carbon, edited by P. L. Walker, 1965.

43. Schalla, R. L., and McDonald, G. E., "Mechanism of Smoke Formation in Diffusion Flames," 5th Symposium (International) on Combustion, pp. 316-323, 1954.

44. Arthur, J. R., and Napier, D. H., "Formation of Carbon and Related Materials in Diffusion Flames," 5th Symposium (International) on Combustion, pp. 303-315, 1954.

45. Gaydon, A. G., and Fairbairn, A. R., "Carbon Formation for C_2H_2 and CO in Discharge Tubes," 5th Symposium (International) on Combustion, pp. 324-328, 1954.

46. Wright, F. J., "Effect of Oxygen on the Carbon Forming Tendencies of Diffusion Flames," Fuel, Vol. 53, No. 4, pp. 232-235, October 1974.

47. Schirmer, R. M., "Effect of Fuel Composition on Particulate Emissions from Gas Turbine Engines," in Emissions from Continuous Combustion Systems edited by , pp. 189-210, 197 .

48. Magnusson, B. F., "An Investigation into the Behavior of Soot in a Turbulent Free Jet C_2H_2 Flame," 15th Symposium (International) on Combustion, pp. 1415-1425, 1974.

49. Wright, F. J., "The Formation of Carbon Under Well-Stirred Conditions," 12th Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, Pa., pp. 867-875, 1968.

50. Wright, F. J., "Carbon Formation Under Wekk-Stirred Conditions, Part II," Combustion and Flame, Vol. 15, pp. 217-222, 1970.

51. Blazowski, W. S., "Combustion Considerations for Future Jet Fuels," 16th Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, Pa., August 1976.

52. Society of Automotive Engineers Committee E-31, "Aerospace Recommended Practice 1179: Aircraft Gas Turbine Smoke Measurement," SAE, N.Y., N.Y., 1970.

53. Champagne, D. L., "Standard Measurement of Aircraft Gas Turbine Exhaust Smoke," ASME Paper No. 71-GT-88, Paper presented at the Gas Turbine Conference and Products Show, Houston, TX, March-April 1971.

54. Blazowski, W. S., "The Impact of JP-4/JP-8 Conversion on Aircraft Engine Exhaust Emissions, AFAPL-TR-76-20, A. F. Aero Propulsion Laboratory, Wright-Patterson AFB, Ohio, May 1976.

55. Bernier, T. R., "T5 and T6 Profile Studies of Fleet Leader Reduced Smoke Combustors," General Electric Company TM-No. 75-214, Aircraft Engine Group, Evandale, OH, March 1975.

56. Reeves, D., "Flame Radiation in an Industrial Gas Turbine Combustion Chamber," National Gas Turbine Establishment Memorandum No. M285, October 1956.

57. Schirmer, R. M., and Aldrich, E. W., "Microburner Studies of Flame Radiation as Related to Hydrocarbon Structure," Phillips Petroleum Co., Research Division Report 3752-64R, for NAVY BUWEPS Contract No. 63-0406-d, May 1964.

58. Quigg, H. T., "Effect of Prevaporized JP-5 Fuel on Combustor Performance," Phillips Petroleum Co., Research andDevelopment Report 6413-72, for Naval Air Systems Command Contract N00019-71-C-0486, October 1972.

59. Lefebvre, A. H., "Radiation from Flames in Gas Turbines and Rocket Engines," 12th Symposium (International) on Combustion, pp. 1247-1254, 1969.

60. MacFarlane, J. J., "Flame Radiation Studies Using a Model Gas Turbine Primary Zone," 12th Symposium (International) on Combustion, pp. 1255-1254, 1969.

61. Marsland, J., Odgers, J., and Winter, J., "The Effects of Flame Radiation on Flame Tube Temperatures," 12th Symposium (International) on Combustion, pp. 1265-1276.

62. Colket, M. B., Stefucza, J. M., Peters, J. E., and Mellor, A. M., "Radiation and Smoke from Gas Turbine Flames, Part II Fuel Effects on Performance," Technical Report No. 12163, TACOM Systems Laboratory, U. S. Army Tank Automotive Command, Warren, Mich., January 1977.

63. Schirmer, R. M., McReynolds, L. A., and Daley, J. A., "Radiation from Flames in Gas Turbine Combustors," SAE Transactions, Vol. 68, pp. 554-561, 1960.

64. Macaulay, R. W., and Shayeson, M. W., "Effects of Fuel Properties on Liner Temperatures and Carbon Deposition in the CJ805 Combustor for Long Life Applications," ASME Paper 61-WA-304, October 1961.

65. McClelland, C. C., "Effects of Jet Fuel Constituents on Combustor Durability," Naval Air Propulsion Test Center Report NAEC-AEL-1736, May 1963.

66. Butze, H. F., and Ehlers, R. C., "Effect of Fuel Properties on Performance of a Single Aircraft Turbojet Combustor," NASA TM-X-71789, Presented at the 1975 WSS/CI Fall Technical Meeting, Palo Alto, CA, October 1975.

67. Stettler, R. J., and Hardin, M. C., "Initial Evaluation of Coal Derived Liquid Fuels in a Low Emission and Conventional Turbine Combustor," General Motors Engineering Publication 6544, April 1976.

68. Jackson, T. A., and Blazowski, W. S., "Fuel Hydrogen Content as an Indicator of Radiative Heat Transfer in an Aircraft Gas Turbine Combustor," Candidate ASME Paper for 1977 Winter Annual Meeting, November 1977.

69. Blazowski, W. S., Fahrenbruck, F. S., and Tackett, L. P., "Evaluation of Future Jet Fuel Combustion Characteristics," AFAPL-TR to be published.

70. Fenimore, C. P., "Formation of NO from Fuel Nitrogen in Ethylene Flames," Combustion and Flame, Vol. 19, pp. 289-296, 1972.

71. Sternling, C. V., and Wendt, J. O. L., "On the Oxidation of Fuel Nitrogen in a Diffusion Flame," AIChE Journal, Vol. 20, No. 1, pp. 81-87, January 1974.

72. Duxbury, J., and Pratt, N. H., "A Shock Tube Study of NO Kinetics in the Presence of H_2 and Fuel-N," 15th Symposium (International) on Combustion, pp. 843-855, 1975.

73. Sarofin, A. F., Williams, G. C., Modell, M., and Slater, S. M., "Conversion of Fuel Nitrogen to NO in Premixed and Diffusion Flames," AIChE Symposium Series, Vol. 68, No. 126, pp. 51-61, 1975.

74. Axworthy, A. E., "Chemistry and Kinetics of Fuel Nitrogen Conversion to NO," AIChE Symposium Series, Vol. 68, No. 126, pp. 43-50, 1975.

75. Bartok, W., Engleman, V. S., Goldstein, R., and del Valle, E. G., "Basic Kinetic Studies and Modeling of NO Formation in Combustion Processes," AIChE Symposium Series, Vol. 68, No. 126, p. 30, 1975.

76. Fenimore, C. P., "Reactions of Fuel-Nitrogen in Rich Flame Gases," Combustion and Flame, Vol. 26, pp. 249-256, 1976.

77. Nelson, H. F., "Nitric Oxide Formation in Combustion," AIAA Journal, Vol. 14, No. 9, pp. 1177-1182, September 1976.

78. Morley, C., "The Formation and Destruction of Hydrogen Cyanide from Atmospheric and Fuel Nitrogen in Rich Atmospheric Pressure Flames," Combustion and Flame, Vol. 27, pp. 187-204, 1976.

79. Haynes, B. S., "Reactions of Ammonia and Nitric Oxide in the Burnt Gases of Fuel-Rich Hydrocarbon-Air Flames," Combustion and Flame, Vol. 28, pp. 81-91, 1977.

80. Longwell, J. P., "Proceedings of the NASA Lewis Research Center Workshop on Hydrocarbon Fuel Technology," to be published.

81. Wilkes, C., and Johnson, R. H., "Effect of Fuel Nitrogen on NO_x Emission from Gas Turbines," The Proceedings of the NO_x Control Technology Seminar, Special Report 39, EPRI, Palo Alto, CA, February 1976.

82. Hung, W. S. Y., "The NO_x Emission Levels of Unconventional Fuels for Gas Turbines," ASME Paper No. 77-GT-16, March 1977.

83. Mosier, S. A., and Pierce, R. M., "Progress in Development of Low-NO_x Gas Turbine Combustors," 69th Annual AIChE Meeting, Chicago, Ill., December 1976.

84. Dilmore, J. A., and Rohrer, W., "Nitric Oxide Formation in the Combustion of Fuels Containing Nitrogen in a Gas Turbine Combustor," ASME Paper No. 74-GT-37, April 1974.

85. Tomlinson, J. G., and Montgomery, L. N., "Elimination of Turbine Erosion in the T56 Turboprop Engine," ASME Paper No. 65-WA/GTT-9, 1965.

86. Dodds, W. J., Peters, J. E., Colket, M. B., and Mellor, A. M., "Preliminary Study of Smoke Formed in the Combustion of Various Jet Fuels," J. Energy, Vol. 1, No. 2, March 1977.

87. Gleason, C. C., and Bahr, D. W., "Experimental Clean Combustor Program Alternate Fuels Addendum Phase II Final Report," NASA-CR-134972, January 1976.

88. Plee, S. L., and Mellor, A. M., "Preliminary Investigation of Flashback in Prevaporizing Premixing Combustor," Paper TI-22 presented at the Western States Section of the Combustor Institute Meeting, 1977.

89. NASA Lewis Research Center," Autoignition of Fuels Program," Request for Proposals, May 25, 1976.

90. Butze, H. F., and Liebert, C. H., "Effect of Ceramic Coating of JT8D Combustor Liner on Maximum Liner Temperatures and Other Combustor Performance Parameters," NASA TM X-73581, NASA Lewis Research Center, Cleveland, Ohio, December 1976.

91. Radcliffe, S. W., and Appleton, J. P., "Soot Oxidation Rates in Gas Turbine Engines," NASA CR-125404, or MIT Fluid Mechanics Laboratory Report No. 71-12, June 1971.

92. Longwell, J. P. and Weiss, M. A., Ind. Eng. Chem., 47, 1634, 1955.

BIBLIOGRAPHY

1. Affens, W. A., Leonard, J. T., McLaren, G. W., and Hazlett, R. N., "Flammability, Ignition, and Electrostatic Properties of Navy Fuels Derived from Coal, Tar Sands, and Shale Oil," 172nd ACS Meeting, Div. Fuel Chem. Preprints, 21, 6, pp. 249-257, 1976.

2. American Petroleum Institute, "Alcohols--A Technical Assessment of Their Application as Fuels," API Publication No. 4261, July 1976.

3. Anderson, S. G., "Fuel Injector for Jet-Stirred Combustors," NASA Tech Briefs, Summer 1977.

4. Antoine, A. C., and Gallagher, J. P., "Synthesis and Analysis of Jet Fuels from Shale Oil and Coal Syncrudes," NASA TM-X-73399, Presented at 82nd AIChE Meeting, August 1976.

5. Appleton, J. P., and Heywood, J. B., "Effects of Imperfect Fuel-Air Mixing in a Burner on NO Formation from Nitrogen in the Air and Fuel," 14th Symposium (International) on Combustion, pp. 777-786, 1973.

6. Arthur, J. R., and Napier, D. H., "Formation of Carbon and Related Materials in Diffusion Flames," 5th Symposium (Int.) on Combustion, pp. 303-

7. Axworthy, A. E., "Chemistry and Kinetics of Fuel Nitrogen Conversion to NO," AIChE Symposium Series, Vol. 71, No. 148, pp. 43-50, 1975.

8. Axworthy, A. E., Schneider, G. R., Shuman, M. D., and Dayan, V. H., "Chemistry of Fuel Nitrogen Conversion to Nitrogen Oxides in Combustion," EPA-600/2-76-039, PB250373, February 1976.

9. Bachmaier, F., Eberius, K. H., and Just, Th., "The Formation of Nitric Oxide and the Detection of HCN in Premixed Hydrocarbon-Air Flames of 1 Atmosphere," Combustion Sci. & Tech., Vol. 7, pp. 77-84, 1973.

10. Ball, R. T., and Howard, J. B., "Electric Charge of Carbon Particles in Flames," 13th Symposium (International) on Combustion, pp. 353-362, 1970.

11. Bartick, H., Kunchal, K., Switzer, D., Bowan, R., and Edwards, R, "The Production and Refining of Crude Shale Oil Into Military Fuels," Final Report on Contract N00014-75-C-0055 for ONR, August 1975.

12. Bartok, W., Engleman, V. S., Goldstein, R, and DelValle, E. G., "Basic Kinetic Studies and Modeling of Nitrogen Oxide Formation in Combustion Processes," AIChE Symposium Series, Vol. 68, No. 126, pp. 30-38.

13. Bartok, W., Heath, C. E., and Weiss, M. A., "Mixing in a Jet-Stirred Reactor," AIChE Journal, Vol. 6, No. 4, pp. 685-687.

14. Beer, J. M., and Howarth, C. W., "Radiation from Flames in Furnaces," 12th Symposium (International) on Combustion, pp. 1205-1217, 1968.

15. Bellon, J., and Summerfield, M., "Comparison of Four Models Describing Combustion of Droplets," 1976 ESS/CI Meeting, November 1976.

16. Benson, R., and Samuelson, G. S., "Oxides of Nitrogen Transformation While Sampling Combustion Products Containing CO, H_2 and Hydrocarbons," WSS/CI 77-7, April 1977.

17. Bhatt, G. L., and Ziegler, E. N., "Effect of Partial Segregation on Conversion in Continuous Stirred Tank Reactors," AIChE Journal, Vol. 23, No. 3, pp. 217-234, May 1977.

18. Boynton, F. P., Ludwig, C. B., and Thomson, A., "Spectral Emissivity of Carbon Particle Clouds in Rocket Exhausts," AIAA Journal, Vol. 6, No. 5, pp. 865-871, May 1968.

19. Bulewicz, E. M., Evans, D. G., and Padley, P. J., "Effect of Metallic Additives on Soot Formation Processes in Flames," 15th Symposium (International) on Combustion, pp. 1461-1470, 1974.

20. Butze, H. F., and Liebert, C. H., "Effect of Ceramic Coating of JT8D Combustor Liner on Maximum Liner Temperature and Other Performance Parameters," NASA-TM-X-73581, December 1976.

21. Butze, H. F., "Effect of Fuel Properties on Performance of a Single Aircraft Turbojet Combustor," NASA-TM-X-71789, October 1975.

22. Callan, R. B., Bendoratis, J. G., Simpson, C. A., and Voltz, S. E., "Upgrading Coal Liquids to Gas Turbine Fuels," Ind. and Eng. Chem., 15, 4, pp. 222-233, 1976.

23. Chakraborty, B. B., and Long, R., "The Formation of Soot and Polycyclic Aromatic Hydrocarbons in Diffusion Flames III--Effect of Additions of Oxygen to Ethylene and Ethane Respectively as Fuels," Comb. and Flame, 12, pp. 469-476, 1968.

24. Clarke, J. S., and Jackson, S. R., "General Considerations in the Design of Combustion Chambers for Aircraft and Industrial Gas Turbines," 1962 SAE Int. Congress and Exposition of Automotive Engineering, Cobo Hall, Detroit, Mich., January 1962.

25. Clarke, R. E., Hunter, T. G., and Garner, F. H., "The Tendency to Smoke of Organic Substances on Burning, Part 1," J. Inst. Pet., 32, pp. 627-642.

26. Clayton, R. M., "Reduction of Gaseous Pollutant Emissions from Gas Turbine Combustors Using Hydrogen-Enriched Jet Fuel, A Progress Report," NASA-TM-33-790, Jet Prop. Labs., Pasadena, CA.

27. Colket, M. B., Stefucza, J. M., Peters, J. E., and Mellor, A. M., "Radiation and Smoke from Gas Turbine Flames, Part II: Fuel Effects on Performance," TACOM TR-12163, Jan. 1977.

28. Cotton, D. H., Friswell, N. J., and Jenkins, D. R., "The Suppression of Soot Emission from Flames by Metal Additives," Comb. and Flame, Vol. 17, pp. 87-98, 1971.

29. D'Alessio, A., DiLorenzo, A., Beretta, F., and Vanitozzi, C., "Optical and Chemical Investigation of Fuel Rich Methane-Oxygen Premixed Flames at Atmospheric Pressure," 14th Symposium (International) on Combustion, pp. 941-953, 1973.

30. D'Alessio, A., DiLorenzo, A., and Sarofin, A. F., "Soot Formation in Methane-Oxygen Flames," 15th Symposium (International) on Combustion, pp. 1427-1438, 1974.

31. D'Alessio, A., DiLorenzo, A., Micera, G., and Beretta, F., "Laser Light Scattering Measurements in the Soot Nucleation Zone of Rich Methane-Oxygen Flames,"

32. Dalzell, W. H., and Sarofin, A. F., "Optical Constants of Soot and Their Application to Heat-Flux Calculations," J. Heat Transfer, Vol. 91, No. 1, pp. 100-104, February 1969.

33. Dalzell, W. H., Williams, G. C., and Hottel, H. C., "A Light-Scattering Method for Soot Concentration Measurements," Combustion and Flame, Vol. 14, pp. 161-170, 1970.

34. Daniels, P. H., "Carbon Formation in Premixed Flames," Combustion and Flame, 4, pp. 45-49, 1960.

35. DeCorso, S. M., Hussey, C. E., and Ambrose, M. J., "Smokeless Combustion in Oil-Burning Gas Turbines," ASME Paper 67-PWR-5, Sept. 1967.

36. DeSoete, G. G., "Overall Reaction Rates of NO and N_2 Formation From Fuel Nitrogen," 15th Symposium (International) on Combustion, pp. 1093-1102, 1975.

37. Dilmore, J. A., and Rohrer, W., "NO_x Formation in the Combustion of Fuels Containing Nitrogen in a Gas Turbine Combustor," ASME Paper 74-GT-37, March 1974.

38. Dryer, F. L., "High Temperature Oxidation of Carbon Monoxide and Methane in a Turbulent Flow Reactor," AFOSR TR-72-1109, March 1972.

39. Durrant, T., Fiorello, S. C. Faitani, J. J., Hochheizer, S., and Lozano, E. R., "Combustor Design Charges Reduce Smoke from Gas Turbine Engines," SAE Journal, 77, 6, pp. 61-64, June 1969.

40. Duxbury, J., and Pratt, N. H., "A Shock Tube Study of NO Kinetics in the Presence of H_2 and Fuel-N," 13th Symposium (International) on Combustion, pp. 843-855, 1975.

41. Eberius, K. H., and Just, Th., "NO Formation in Fuel Rich Flames: A Study of the Influence of the Hydrocarbon Structure,"

42. Eberius, H., Just, Th., and Rittwagen, H., "NO Formation in the Primary Reaction Zone of Low Pressure Flames," European Section of the Combustion Institute, Sept. 1975.

43. Eberius, K. H., and Just, Th., "NO Formation in Fuel Rich Flames: A Study of the Influence of the Hydrocarbon Structure," AGARD Conference Proceedings 125, 16-1, 1973.

44. Edelman, R. B., and Harsha, P. T., "Current Status of Laminar and Turbulent Gas Dynamics in Combustors," CSS/CI paper, NASA Lewis Res. Center, Cleveland, Ohio, March 28-30, 1977.

45. Eisen, F. S., "Preparation of Gas Turbine Fuel From Synthetic Crude Oil Derived from Coal, Phase II. Final Report," U. S. Navy Contract N00014-74-C-0568, Mod. P00001, AD-A007923, February 1975.

46. Evangelista, J. J., Shinnar, R., and Katz, S., "The Effect of Imperfect Mixing on Stirred Combustion Reactors," 12th Symposium (International) on Combustion, pp. 901-912, 1968.

47. Exxon Co. U.S.A., "Data Book for Designers."

48. Faeth, G. M., "Current Status of Droplet and Liquid Combustion," CSS/CI Spring Meeting, 1977.

49. Faitani, J. J., "Smoke Reduction in Jet Engines Through Burner Design," SAE Paper No. 680348, May 1968.

50. Fear, J. S., "The NASA Pollution-Reduction Technology Program for Small A/C Engines--A Status Report," AIAA Paper No. 76-616, July 1976.

51. Fenimore, C. P., "Reactions of Fuel Nitrogen in Rich Flame Gases," Combustion and Flame, Vol. 26, pp. 249-256, 1976.

52. Fenimore, C. P., "Formation of NO from Fuel Nitrogen in C_2H_4 Flames," Combustion and Flame, 19, pp. 289-296, 1972.

53. Fenimore, C. P., Jones, G. W., and Moore, G. E., "Carbon Formation in Quenched Flat Flames @ 1600 K," 6th Symposium (International) on Combustion, pp. 242-246,

54. Fenimore, C. P., and Jones, G. W., "Oxidation of Soot by Hydroxyl Radicals," J. Phys. Chem., Vol. 71, No. 3, pp. 593-597, Feb. 1967.

55. Foster, P. J., "Calculation of the Optical Properties of Dispersed Phases," Combustion and Flame, Vol. 7, pp. 277-282, Sept. 1963.

56. Fristrom, R. M., "Flames as Chemical Reactors," 2nd International Symposium on Chem. Rxn. Dynamics, Padua, Italy, Dec. 1975.

57. Friswell, N. J., "Emissions from Gas-Turbine-Type Combustors," Emissions from Combustion Systems, pp. 161-182,

58. Ganji, A.J., Branch, M. C., Oppenheim, A. K., "Gas Turbine Combustor Stabilization by Heat Recirculation," AIAA Journal, Vol. 14, No. 6, pp. 809-812, 1976.

59. Gaydon, A. G., and Fairbairn, A. R., "Carbon Formation from C_2H_2 and CO in Discharge Tubes," 5th Symposium (International) on Combustion, pp. 324-328.

60. Giammar, R. D., Weller, A. E., Locklin, D. W., and Kruase, H. H., "Experimental Evaluation of Fuel Oil Additives for Reducing Emissions and Increasing Efficiency of Boilers," EPA-600/2-71-0086, Jan. 1977.

61. Gill, D. W., "Review No. 182--Luminosity and Soot Formation in Hydrocarbon Flames," The British Coal Utilization Research Ass'n. Monthly Bulletin, Vol. XXII, No. 12, Part II, pp. 487-506, Nov.-Dec. 1958.

62. Glassman, I., Dryer, F. L., and Cohen, R., "Combustion of Hydrocarbons in an Adiabatic Flow Reactor: Some Considerations and Overall Correlations of Reaction Rage," Central and Western State CI. Joint Spring Tech. Meeting, San Antonio, Texas, April 21-22, 1975.

63. Glassman, I., Dryer, F. L., and Cohen, R., "Studies of Hydrocarbon Oxidation in a Flow Reactor," 2nd International Symposium on Chem. Rxn. Dynamics, Padua, Italy, Dec. 1975.

64. Gleason, C. C., and Niedzwiecki, R. W., "Results of the NASA/GE ECCP," AIAA Paper No. 76-763, July 1976.

65. Gleason, C. C., and Bahr, D. W., "Experimental Clean Combustor Program: Alternate Fuels Addendum, Phase II Final Report," NASA-CR-134972, R76AEG268 (G. E. Rep't. No.).

66. Godridge, A. M., and Hammond, E. G., "Emissivity of a Very Large Residual Fuel Oil Flame," 12th Symposium (International) on Combustion, pp. 1219-1228, 1968.

67. Haebig, J. E., Davis, B. E., and Dzuna, E. R., "Preliminary Small-Scale Combustion Tests of Coal Liquids," Env. Sci. Tech., 10, 3, pp. 243-247, March 1976.

68. Hardesty, D. R., and Weinberg, F. J., "Electrical Control of Particulate Pollutants from Flames," 14th Symposium (International) on Combustion, pp. 907-918, 1973.

69. Haynes, B. S., "Production of Nitrogen Compounds from Molecular Nitrogen in Fuel-Rich Hydrocarbon Air Flames," Fuel, Vol. 56, pp. 199-203, April 1977.

70. Haynes, B. S., "Reactions of Ammonia and NO in the Burnt Gases of Fuel-Rich Hydrocarbon-Air Flames," Combustion and Flame, Vol. 28, pp. 81-91, 1977.

71. Hazlett, R. N., Hall, J. M., and Solash, J., "Properties and Composition of Jet Fuels Derived from Alternate Energy Sources. Part 1. Background and N-Alkane Content," ACS Div. Fuel Chem. Preprint, Vol. 21, No. 6, pp. 219-230, 1976.

72. Hefner, W. J., "Alternate Fuels Capability of Gas Turbines in the Process Industry," ASME Paper 76-GT-119, March 1976.

73. Hill, W. E., and Dibelius, N. R., "Measurement of Flame Temperature and Emittance in Gas Turbine Combustors," J. Eng. for Power, Vol. 92, No. 3, pp. 310-314, 1970.

74. Hilliard, J. C., and Wheeler, R. W., "Catalyzed Oxidation of NO to NO_2," Combustion of Flame, 29, pp. 13-19, 1977.

75. Hilt, M. B., Fenimore, C. P., and Johnson, R. H., "Hydrocarbon Combustion Smoke and its Elimination from Heavy Duty Gas Turbines," ASME Paper 70-PWR-14, Sept. 1970.

76. Homann, K. H., "Carbon Formation in Premixed Flames," Combustion and Flame, 11, pp. 265-287, 1967.

77. Hottel, H. C., and Broughton, F. P., "Determination of True Temperature and Total Radiation from Luminous Gas Flames," Ind. Eng. Chem., 4, pp. 166-175, 1932.

78. Howard, J. B., "On the Mechanism of Carbon Formation in Flames," 12th Symposium (International) on Combustion, pp. 877-887, 1968.

79. Hung, W. S. Y., "The NO_x Emission Levels of Unconventional Fuels for Gas Turbines," ASME Paper No. 77-GT-16, 1977.

80. Iverach, D., Basden, K. S., and Kirov, N. Y., "Formation of NO in Fuel-Lean and Fuel-Rich Flames," 14th Symposium (International) on Combustion, pp. 767-775, 1973.

81. Jaarsma, F., "Impact of Future Fuels on Military Aero Engines," AGARD Annual Meeting, 1974.

82. Johnson, T. R., and Beer, J. M., "Radiative Heat Transfers in Furnaces: Further Development of the Zone Method of Analysis," 14th Symposium (International) on Combustion, pp. 639-649, 1973.

83. Juhasz, A. J., and Marek, C. J., "Combustor Liner Film Cooling in the Presence of High Free-Stream Turbulence," NASA TN-D-6360, July 1971.

84. Khristich, V. A., and Litoshenke, V. N., "The Coorelation of the Characteristics of Flameout and Ignition of Flames During Diffusion Combustion of Fuel Behind Systems of Angled Stabilizers," FTD-MT-24-1744-71.

85. Klapatch, R. D., and Vitti, G. E., "Gas Turbine Combustor Test Results and Combined Cycle System," Combustion, 45, 10, pp. 35-78, April 1974.

86. Kollrack, R., "Model Calculations of the Combustion Product Distributions in the Primary Zone of a G.T. Combustor," ASME paper 76-WA/GT-7, Dec.

87. Kollrack, R., and Aceto, L. D., "Radical Overshoot Phenomena in Liquid Fueled Gas Turbine Combustors," ASME Paper No. 77-GT-5, 1977.

88. Kramlich, J. C., and Malte, P. C., "Modeling and Experimentation of Sample Probe Effects on Pollutant Gases Drawn from Flame Zones," WSS/CI Spring Meeting, 1977.

89. Kukin, I., and Bennett, R. P., "Chemical Reduction of SO_3, Particulates, and NO_x Emissions," J. Inst. Fuel, Vol. 50, pp. 41-46, 1977.

90. Lee, K. B., Thring, M. W., and Beer, J. M., "On the Rate of Combustion of Soot in a Laminar Soot Flame," Combustion and Flame, Vol. 6, pp. 137-145, Sept. 1962.

91. Lefebvre, A. H., "Radiation from Flames in Gas Turbines and Rocket Engines," 12th Symposium (International) on Combustion, pp. 1247-1253.

92. Liebert, C. H., and Stepka, F. S., "Ceramic Thermal-Barrier Coatings for Cooled Turbines," J. Aircraft, Vol. 14, No. 5, pp. 487-493, May 1977.

93. Liebert, C. H., and Stepka, F. S., "Ceramic Thermal-Barrier Coatings for Cooled Turbines," AIAA Paper 76-729, July 1976.

94. Linford, R. M. F., Dillon, C. F., and Trumble, T. M, "Optical Emissions from Burning Jet Fuel," J. Aircraft, Vol. 14, No. 5, pp. 481-486, May 1977.

95. Locklin, D. W., "Small Oil Burners--A Review of Some Recent Developments,' ASMA Paper 69-WA/Fu-5, 1969.

96. Locklin, D. W., and Barrett, R. E., "Guidelines for Residential Oil-Burner Adjustment to Minimize Pollutant Emissions," 70th Annual APCA Meeting, Paper No. 77-24.3, Toronto, Canada, June 20-24, 1977.

97. Longwell, J. P., Frost, E. E., and Weiss, M. A., "Flame Stability in Bluff Body Recirculation Zones," Ind. Eng. Chem., Eng. and Proc. Dev., Vol. 45, pp. 1629-1633, 1953.

98. McClelland, C. C., "Effects of Jet Fuel Constituents on Combustor Durability," NAEC-AEL-1736, May 1963.

99. Macaulay, R. W., and Shayeson, M. W., "Effects of Fuel Properties on Liner Temperatures and Carbon Deposition in the CJ805 Combustor for Long-Life Applications," ASME Paper 61-WA-304, Nov. 1961.

100. Macfarlane, J. J., Holderman, F. H., and Whiteher, F. S. E., "Soot Formation Rates in Premixed C_5 and C_6 Hydrocarbon-Air Flames at Pressures up to 20 Atm.," Comb. and Flame, 8, pp. 215-229, 1964.

101. MacFarlane, J. J., "Flame Radiation Studies Using a Model Gas Turbine Primary Zone," 12th Symposium (International) on Combustion, pp. 1255-1264,

102. Maesawa, M., Tanaka, Y., Ogisu, Y., and Tsukamoto, Y., "Radiation from the Luminous Flames of Liquid Fuel Jets in a Combustion Chamber," 12th Symposium (International) on Combustion, pp. 1229-1237, 1968.

103. Magnussan, B. F., "An Investigation into the Behavior of Soot in a Turbulent-Free Jet C_2H_2-Flame," 13th Symposium (International) on Combustion, pp. 1415-1425, 1974.

104. Manny, E. H., Bartok, W., Crawford, A. R. Hall, R. E., and Vatsky, J., "Studies of Waterwall Corrosion with Staged Combustion of Coal,"

105. Marinchenko, N. I., Chertko, Y. B., and Piskunov, V. A., "Scale Formation in Turbojet Engines," FTD-HT-23-825-67, August 1967.

106. Marsland, J., Odgers, J., and Winter, J., "The Effects of Flame Radiation on Flame-Tube Metal Temperatures," 12th Symposium (International) on Combustion, pp. 1265-1276.

107. May, W. R., Zetlmeisl, M. J., Annend, R. R. and Laurence, D. F., "High Temperature Corrosion in Gas Turbines and Steam Boilers by Fuel Impurities: Part VIII. Evaluation of the Effects of Mn, Ca, and Several Heavy Metals on Corrosion and Slag Formation," ACS Div. Fuel Chem. Preprints, 21, 1, pp. 1-12, April 1976.

108. Mayo, F. R., Kirshen, N., Richardson, H., and Stringham, R., "The Chemistry of Fuel Deposits and Their Precursors," Contract N00019-72-C-0161.

109. Mellor, A. M., Prog. Rep. on: "Characteristic Time Correlation for Pollutant Emissions from Aircraft-Type Gas Turbine Flames," March 1977.

110. Merryman, E. L., Hazard, H. R., Barnett, R. E., and Levy, A., "Recent Studies of the Conversion of Fuel Nitrogen to NO_x," CSS/CI Spring Meeting, 1974.

111. Merryman, E. L., and Levy, A., "Nitrogen Oxide Formation in Flames: The Roles of NO_2 and Fuel Nitrogen," 15th Symposium (International) on Combustion, pp. 1073-1083, 1975.

112. Miles, G. A., "A Well-Stirred-Reactor Investigation of the Combustion of Propane with Vitiated Air," 13th Symposium (International) on Combustion, pp. 483-487, 1970.

113. Morley, C., "The Formation and Descruction of Hydrogen Cyanide from Atmospheric and Fuel Nitrogen in Rich Atmospheric-Pressure Flames," Combustion and Flame, 27, pp. 189-204, 1976.

114. Mosier, S. A., and Pierce, R. M., "Progress in Development of Low-NO_x Gas Turbine Combustors," Presented at the 69th Annual AIChE Meeting, Dec. 1976.

115. Mularz, E. J., "Results of the Pollution Technology Program for Turboprop Engines," AIAA Paper No. 76-760, July 1976.

116. Muller-Dethlefs, K., and Schlader, A. F., "The Effect of Steam on Flame Temperature, Burning Velocity and Carbon Formation in Hydrocarbon Flames," Combustion and Flame, 27, 2, pp. 205-215, 1976.

117. Mulvihill, J. N., and Phillips, L. F., "Breakdown of Cyanogen in Fuel-Rich $H_2/N_2/O_2$ Flames," 15th Symposium (International) on Combustion, pp. 1113-1122, 1975.

118. Mumford, S. E., Hung, W. S. Y., and Singh, P. P., "A Potential Low NO_x Emission Combustor for Gas Turbines Using the Concept of Hybrid Combustion," ASME Paper No. 77-GT-15, 1977.

119. Neitzel, R. E., "Comparisons of Alternate Energy Efficient Engines for Subsonic Transports as Affected by Engine Technology Improvements," AIAA Paper No. 76-770, July 1976.

120. Nelson, A. W., "Development of a Low Smoke Combustor for the JT3D Engine," SAE Paper No. 740484, May 1974.

121. Nelson, H. F., "NO Formation in Combustion," AIAA Journal, Vol. 14, No. 9, pp. 1177-1182, Sept. 1976.

122. Norgren, C. T., "Determination of Primary-Zone Smoke Concentrations from Spectral Radiance Measurements in Gas Turbine Combustors," NASA-TN-D-6410, July 1971.

123. Norgren, C. T., and Ingebo, R. D., "Effects of Prevaporized Fuel on Exhaust Emissions of an Experimental Gas Turbine Combustor," NASA-TM X-68194, March 1973.

124. Norgren, C. T., and Ingebo, R. D., "Particulate Exhaust Emissions from an Experimental Combustor," NASA TM X-3254, June 1975.

125. Norgren, C. T., "Comparison of Primary-Zone Combustor Liner Wall Temperatures with Calculated Predictions,"

126. Odgers, J., and Cobon, A., "The Energy Release to Static Gas From a 12-Joule High Energy Ignition System," ASME Paper No. 77-GT-18, 1977.

127. Osgerby, I. T., "An Efficient Numerical Method for Stirred-Reactor Calculations," AEDC-TR-72-164 or AFOSR-TR-72-0910, AD-751462, Nov. 1972.

128. Palmer, H. B., and Cullis, C. F. "Chapter 5: The Formation of Carbon from Gases," Chemistry and Physics of Carbon, edited by P. L. Walker, 1965.

129. Pasion, A. J., and Thomas, I., "Preliminary Analysis of Aircraft Fuel Systems for Use with Broadened Specification Jet Fuels," NASA-CR-135198, May 1976.

130. Patil, P. B., Sichel, M., and Nicholls, J. A., "Analysis of Spray Combustion in a Research Gas Turbine Combustor," CSS/CI Spring Meeting, NASA LeRC, March 28-30, 1977.

131. Peterson, P. R., Samuelson, G. S., "Emission Behavior of Aerodynamically-Stabilized, Lean, Premixed Combustion," WSS/CI 77-10, April 1977.

132. Pillsbury, P. W., and Lin, S. S., "Recent Tests of Industrial G. T., Combustors Fueled with Simulated Low Heating Value Coal Gas," ASME Paper 76-WA/GT-3, Dec. 1976.

133. Plee, S. L., and Mellor, A. M., "Preliminary Investigation of Flashback in Prevaporizing/Premixing Combustors," WSS/CI 77-22, April 1977.

134. Pontello, A. P., "Synthetic Jet Fuels Require Improved Filtration, Filtration and Separation, pp. 561- , Nov./Dec. 1976.

135. Porter, G., "Flash Photolysis and Spectroscopy--A New Method for the Study of Free Radical Reactions," Proc. R. Soc., 200A, pp. 284-300.

136. Pratt, D. T., and Malte, P. C., "Formation of Thermal and Prompt NO_x in a Jet Stirred Combustor," AIChE Symposium Series, Vol. 71, No. 148, pp. 150-157, 1975.

137. Quigg, H. T., "Effect of Prevaporized JP-5 Fuel on Combustor Performance," Phillips Petroleum Co. R&D Report 6413-72, for Naval Air Systems Command, Contract N00019-71-C-0486, Oct. 1972.

138. Quigg, H. T., "Reduction of Pollutants from A/C Turbines by Fuel Selection and Prevaporization," Final Report U. S. Navy Contract N00140-72-C-6969, AD-769099.

139. Radcliffe, S. W., and Appleton, J. P., "Soot Oxidation Rates in Gas Turbine Engines," MIT Fluid Mechanics Lab Report No. 71.12, NASA-CR-125404, June 1971.

140. Raymond, L., "Future Fuels for Automotive Gas Turbines," SAE Paper 660766, October 1966.

141. Reeves, D., "Flame Radiation in an Industrial Gas Turbine Combustion Chamber," Nat'l. Gas Turbine Establishment, Memo No. M285, October 1956.

142. Roberts, R., Peduzzi, A., and Niedzwiecki, R. W., "Low Pollution Combustor Designs for CTOL Engines--Results of the ECCP," AIAA Paper 76-762, July 1976.

143. Roberts, R., Fiorentino, A. J., and Diehl, L., "The Pollution Reduction Technology Program for Can-Annular Combustor Engines--Description and Results," AIAA Paper 76-761, July 1976.

144. Robertson, D. J., Groth, R. H., Gardiner, D. G., and Glastris, A. G., "Stability and Analysis of NO in N_2," JAPCA, Vol. 27, No. 8, pp. 779-780, August 1977.

145. Roffe, G., "Development of a Catalytic Combustor Fuel/Air Carburetion System," AFAPL-TR-77-19, March 1977.

146. Rubins, P. M., and Marchionna, N. R., "Evaluation of NO_x Prediction-Correlation Equations for Small Gas Turbines," AIAA Paper No. 76-612, July 1976.

147. Rudakor, Ya. D., Geller, Z. I., Gaponenko, A. M., and Rudakov, G. Ya, "Experimental Investigation of Atomization of Liquid by Acoustic Atomizers," Thermal Eng., 19, 10, pp. 118-121, 1972.

148. Satooja, K. C., "Combustion Control by Novel Catalytic Means," Nature, 240, pp. 350-351, 1972.

149. Samuelson, G. S., and Harman, J. N., "Chemical Transformation of Nitrogen Oxides While Sampling Combustion Products," J. APCA, Vol. 27, No. 7, pp. 648-655, July 1977.

150. Sarofim, A. F., Williams, G. C., Modell, M., and Slater, S. M., "Conversion of Fuel Nitrogen to NO in Premixed and Diffusion Flames," AIChE Symposium Series, Vol. 71, No. 148, pp. 51-61, 1975.

151. Schalla, R. L., and McDonald, G. E., Mechanism of Smoke Formation in Diffusion Flames," 5th Symposium (International) on Combustion, pp. 316-323,

152. Schirmer, R. M., "Effect of Fuel Composition on Particulate Emissions from Gas Turbine Engines," Emissions from Continuous Combustion Systems, pp. 189-210.

153. Schirmer, R. M., and Aldrich, E. W., "Microburner Studies of Flame Radiation as Related to Hydrocarbon Structure," Progress Report No. 4 for Navy BOWEPS Contract NO_w 63-0406-I, Phillips Research Division Report 3752-64R, May 1974.

154. Shirmer, R. M., McReynolds, L. A., and Daley, J. A., "Radiation from Flames in Gas Turbine Combustors," SAE Transactions, 68, pp. 554-561, 1960.

155. Schmitz, R. A., "Multiplicity, Stability and Sensitivity of States in Chemically Reacting Systems--A Review," Adv. Chem. No. 148, Chemical Reaction Engineering, pp. 156-211, 1975.

156. Shabad, L. M., and Smirnov, G. A., "Aircraft Engines as a Source of Carcenogenic Pollution of the Environment (Benzo(α)Pyrene Studies)," Atmospheric Environment, Vol. 6, pp. 153-164, 1972.

157. Sheppard, C. G. W., "A Simple Model for CO Oxidation in Gas Turbine Combustors," Comb. Sci. and Tech., Vol. 11, pp. 49-56, 1975.

158. Siddall, R. G., and McGrath, I. A., "The Emissivity of Luminous Flames," 9th Symposium (International) on Combustion, pp. 102-110, 1963.

159. Silverman, S., "The Determination of Flame Temperature by Infrared Radiation," J. Optical Soc. of America, Vol. 39, No. 4, pp. 275-277, April 1949.

160. Siminski, V. J., and Wright, F. J., "Research on Methods of Improving the Combustion Characteristics of Liquid Hydrocarbon Fuels," AFAPL-TR-72-24.

161. Siminski, V. J., "Hydrocarbon Fuel Study Program Final Technical Report," NWC TP 5468.

162. Simmons, H. C., "The Correlation of Drop Size Distributions in Fuel Nozzle Sprays. Part II: The Drop Size/Number Distribution," ASME Paper 76-NA/GT-10.

163. Simmons, H. C., "The Correlation of Drop Size Distributions in Fuel Nozzle Sprays. Part I: The Drop Size/Volume Fraction Distribution," ASME Paper 76-WA/GT-9.

164. Singh, S., Stacy, L. E., Malte, P. C., and Tripp, B. I., "Optical and Probe Sampling Concentration Measurements for Propane/Air and Methane/Air Combustion in Jet-Stirred Reactor," WSS/CI Spring Meeting, 1977.

165. Sjogran, A., "Soot Formation by Combustion of an Atomized Liquid Fuel," 14th Symposium (International) on Combustion, pp. 919-927, 1973.

166. Society of Automotive Engineers, "Aerospace Recommended Practice 1179--Aircraft Gas Turbine Engine Smoke Measurement," Issued May 4, 1970.

167. Society of Automotive Engineers, "Aerospace Recommended Practice (ARP) 1256--Procedure for the Continuous Sampling and Measurement of Gaseous Emissions from Aircraft Turbine Engines," Issued October 1, 1971.

168. Stehling, F. C., Frazee, J. D., and Anderson, R. C., "Carbon Formation from Acetylene," 6th Symposium (International) on Combustion, pp. 247-254,

169. Sternling, C. V., and Wendt, J. O. L., "On the Oxidation of Fuel Nitrogen in a Diffusion Flame," AIChE Journal, Vol. 20, No. 1, pp. 81-87, Jan. 1974.

170. Stettler, R. J., and Hardin, M. C., "Initial Evaluation of Coal-Derived Liquid Fuels in a Conventional Turbine Combustor," Comb. Inst. Central States Spring Meeting, April 5-6, 1976.

171. Street, J. C., and Thomas, A., "Soot Formation in Premixed Flames," Fuel, 34, pp. 4-36, 1955.

172. Stull, V. R., and Plass, G. N., "Emissivity of Dispersed Carbon Particles," J. Optical Soc. of America, Vol. 50, No. 2, pp. 121-129, Feb. 1960.

173. Tate, R. W., and Olson, E. O., "Spray Droplet Size of Pressure Atomizing Burner Nozzles," ASHRAE Jor, Vol. 4, No. 3, pp. 39-42, Nov. 1962.

174. Taylor, W. G., et al, "Reducing Smoke from Gas Turbines," Mechanical Engineering, 90, 7, pp. 29-35, July 1968.

175. Teineira, D. P., White, D. J., and Ward, M. E., "Evaluation of a Premixed, Prevaporized Gas Turbine Combustor for No. 2 Distillate," ASME Paper No. 77-GT-69.

176. Tesner, P. A., "Formation of Dispersed Carbon by Thermal Decomposition of Hydrocarbons," 7th Symposium on Combustion, 1959.

177. Thomas, A, "Carbon Formation in Flames," Comb. and Flame, Vol. 6, pp. 46-62, March 1962.

178. Thring, M. W., Foster, P. J. McGrath, I. A., and Ashton, J. S., "Prediction of the Emissivity of Hydrocarbon Flames," International Developments in Heat Transfer, ASME, pp. 796-803, 1963.

179. Thring, M. W., and Beer, J. M., "Theory and Practice of Methods for Measurement of Temperatures for Industrial-Sized Flame", Symposium on Techniques for Temperature Measurement (Institute of Mechanical Engineering), 1962.

180. Tomlinson, J. G., and Montgomery, L. N., "Elimination of Turbine Ension in the T56 Turboprop Engine", ASME Paper No. 65-WA/BTP-9, November, 1965.

181. Tourin, R. H., Grossman, M., "Note on Monochromatic Radiation Pyrometry for Measuring Flame and Exhaust Gas Temperature", Combustion and Flame, Volume 2, pp. 330-332, 1958.

182. Tourin, R. J., "Chapter 3: Radiometric Methods of Gas Pyrometry", Spectroscopic Gas Temperature Measurement, Elsevier Publ. Co., New York, 1966.

183. Tourin, R. J., "Recent Developments in Gas Pyrometry by Spectroscopic Methods", ASME Paper No. 63-WA-252, November, 1963.

184. Tu, C. M., Davis, H., and Hottel, H. C., "Combustion Rate of Carbon: Combustion of Spheres in Flowing Gas Streams", Ind. Eng. Chem., Volume 26, Number 7, pp. 749-757, July, 1934.

185. Vranos, A., and Taback, E. D., "Combustion Product Distributions in the Primary Zone of a Gas Turbine Combustor", Combustion and Flame, pp. 129-131, 1976.

186. Wersborg, B. L., Howard, J. B., and Williams, G. C., "Physical Mechanisms in Carbon Formation in Flames", 14th Symposium (International) on Combustion, pp. 929-939, 1973.

187. Wersborg, B. L., Yeung, A. C., and Howard, J. B., "Concentration and Mass Distribution of Charged Species in Sooting Flames", 15th Symposium (International) on Combustion, pp. 1439-1448, 1974.

188. Williams, G. C., Hottel, H. C., and Morgan, A. C., "The Combustion of Methane in a Jet-Mixed Reactor", 12th Symposium (International) on Combustion, pp. 913-925, 1968.

189. Williamson, R. C., and Stanforth, C. M., "Measurement of Jet Engine Combustion Temperatures by the Use of Thermocouples and Gas Analysis", SAE Paper No. 690433, April, 1969.

190. Wolfhard, H. B., and Parker, W. G., "A New Technique for the Spectroscopic Examination of Flames at Normal Pressures", Proc. Phys. Soc., Volume 62A, pp. 722-730, 1949.

191. Wormek, J. J., "Computer Modeling of Turbulent Combustion in a Longwell Jet-Stirred Reactor", University Microfilms 77-2891, Washington State University, Ph.D., 1976.

192. Wright, F. J., "Effect of Oxygen on the Carbon-Forming Tendencies of Diffusion Flames", Fuel, 53.4, pp. 232-235, October, 1974.

193. Wright, F. W., "The Formation of Carbon Under Well Stirred Conditions", 12th Symposium on Combustion, pp. 867-875, 1968.

194. Wright, F. W., "Carbon Formation Under Well-Stirred Conditions - Part II", Combustion and Flame, 15, pp. 217-222, 1970.

195. Wright, F. J., "The Oxidation of Soot by O Atoms", 15th Symposium (International) on Combustion, pp. 1449-1460, 1974.

196. Yamanaka, K., Nagato, K., "Preliminary Study of Low Emission Gas Turbine Combustor with Air-Blast Fuel Atomizer", J. Eng. for Power, pp. 15-22, January, 1976.

197. Zaba, T., "Low Grade Fuel Used in Gas Turbines", The Oil and Gas Journal, April 25, 1977.

198. Aiba, T., "Liner Cooling of an Aircraft Gas Turbine Combustor", ASME Paper No. 75-HT-3, Aug. 1975.

199. Akira, I., Toyuguchi, M., "Gelatinous Hydrocarbon Fuels with Low NO_x and Smoke Formation", Japan, Kokai 74 27,502 (Patent), Vol. No. 75, Issue No. 29606, p. 6, March 25, 1975.

200. Altioicker, E. R., Fredette, P. E., and Shen, T., "Pollutants from Fuel Oil Combustion and the Effect of Additives", 64th APCA Ann. Meeting, Reprint No. 71-74, p. 23, June, 1971.

201. Ambrosio, M., Beretta, F., "Analytical Techniques in the Study of Pollutants Evolution in Rich Methane Oxygen Flames", Riv. Combust. Vol. 29, Issue No. 7-8, pp. 337-348, 1975.

202. Armstrong, R. B., "Carbon Black Formation in a Counter Flow Diffusion Flame", Univ. Minn. Diss., Diss. Abstr. Int. B V35, N. 12, 5868B, p. 157, 1974.

203. Atas, F., Page, F. M., "The Oxidation of Soot in Fuel Rich Flames", ACS Div. Fuel Chem Preprints, Vol. 22, Issue No. 1, pp. 130-134, Feb. 1977.

204. Bagnetto, L., "Smoke Abatement in Gas Turbines. Part 2: Effects of Fuels, Additives and Operating Conditions...", Phillips Petroleum Co. Report 5127-68 - PC.2, Sept. 1968.

205. Balakrishan, A., Edwards, D. K., "Radiative Flame Cooling for Reduction of NO_x Emission", J. Heat Transfer, Vol. 96, Issue No. 1, pp. 37-42, 1974.

206. Bentley, H. T., Bomar, B. W., "Development of a Laser Velocimiter System for Flame Studies", EPA-600/2-77-007, Jan. 1977.

207. Bittmes, J. D., "Formation of Soot and Polycyclic Aromatic Hydrocarbon in Combustion Systems", J. Air Poll. Cont. Assn., Vol. 26, Issue No. 2, pp. 111-115, Feb. 1976.

208. Blokh, A. G., Modzalevskaya, M. L. and Galitskaya, M. N., "Scattering of Thermal Radiation by Carbon Particles in Flames", Thermal Engineering, Vol. 19, Issue No. 2, pp. 44-47, Feb. 1972.

209. Bocca, P., Fontana, M., "Chemical Factors Influencing Particulate Emissions from Fuel Oil", *Riv. Combustion*, Volume 30, Issue No. 8, pp. 239-252, Aug. 1976.

210. Bowser, R. J., Weinberg, F. J., "Electrons and the Emission of Soot From Flames", *Nature*, Volume 249, Issue No. 5455, pp. 339-341, 1974.

211. Bowser, R. J., Weinburg, F. J., "Chem-Ionization During Pyrolysis", *Comb. & Flame*, Volume 27, Issue No. 1, pp. 21-32, Aug. 1976.

212. Buckius, R. O., Tien, C. L., "Infrared Flame Radiation", *Int. J. Heat/* Mass Transfer, Volume 20, Issue No. 2, pp. 93-106, Feb. 1977.

213. Campagne, L., "Partial Combustion of Carbonaceous Fuels to Gases with Substantially Lower Soot Content", *Ger Offen*, p. 22.

214. Caretto, L. S., "Modeling The Gas Phase Kinetics of Fuel Nitrogen", *Western States Section CI Spring Meeting, 1976*, p. 32, April, 1976.

215. Chakraborty, B. B., Long, R., "The Formation of Soot and Polycyclic Aromatic Hydrocarbons in C_2H_4 Diffusion Flames", *Combustion and Flame*, Volume 12, Issue No. 2, pp. 168-170, April, 1968.

216. Chakraborty, B. B., Long, R., "The Formation of Soot and Polycyclic Aromatic Hydrocarbons in Diffusion Flames - I and II", *Combustion and Flame*, Volume 12, Issue No. 3, pp. 226-242, June, 1968.

217. Chang, S. G., Norakov, T., "Formation of Pollution Particulate Nitrogen Compounds 67 NO-Soot and Ammonia-Soot Gas-Particle Surface Reaction", *Atmos. Environ.*, Volume 9, Issue No. 5, pp. 495-504, 1975.

218. Cox, R. K., "Spraying Droplets to Order", *Automation (Clevc)*, pp. 21-28.

219. Crittenden, B. D., Long, R., "Diphenylene Oxide and Cyclopentacenaphthylene in Flame Soots", *Env. Sci.and Tech.*, Volume 7, Issue No. 8, pp. 742-744, 1973.

220. Cullis, C. F., "Role Acetylenic Species in Carbon Formation", *ACS Symp. Series*, Volume 21, pp. 348-357, 1976.

221. Dalessio, A., Beretta, F., and DiLorenzo, A., "Kinetics of Formation of Polycyclic Aromatic Hydrocarbons and Soot in Premixed Flames", *Chem. Ind.*, Volume 58, Issue No. 7, pp. 525-526, July, 1976.

222. deSoete, G. G., "Overall Mechanism of NO_x Formation from Ammonia and Amines Added to Premixed Hydrocarbon Flames", *Combus. Inst. Eur. Symposium*, Paper 73, pp. 439-444, 1973.

223. DiLorenzo, A., Masi, S., "Chemical Investigations on Soot-Forming Premixed Flames", *Termotechica*, Volume 29, Issue No. 11, pp. 590-596, 1975.

224. DiLorenzo, A., et al, "Spectral and Chemical Studies of Soot Forming Premixed Flames", *Arch. Procisow Spalania*, Volume 5, Issue No. 2, pp. 189-201, 1974.

225. DiLorenzo, A., Masi, S., and Guerrinic, R., "Chemical Characteristics of Soot Collected in an Industrial Diffusion Flame", Riv. Combustion, Volume 30, Issue No. 2, pp. 46-51, Feb. 1976.

226. Dugwell, D. R., Foster, P. J., "Carbon Formation from Methane in Combustion Products", Carbon, Volume 11, Issue No. 5, pp. 455-467, Oct. 1973.

227. Duxbury, J., Pratt, N. H., "Shock Tube Investigation of the Fuel Nitrogen-NO_x Problem", Comb. Inst. Eur. Symposium, Paper No. 732, pp. 433-438, Sept. 1973.

228. Dzuna, E. R., "Combustion Tests on Shale Oil Fuels", Combust. Inst. Cen. States Sec. Spring Meeting, 1976, Columbus, Ohio, 1976.

229. Erickson, W.D., Williams, G. C., and Hottel, H. C., "Light Scattering Measurements in a Premixed Laminar Benzene-Air Flame", Combustion and Flame, Volume 8, Issue No. 2, pp. 127-132, June, 1964.

230. Essenhigh, R., Kurylko, L., "The Unsteady and Steady Combustion of Carbon", Penn State Univ. Reg. FS69-2(U), Volume AD-699531, June 1969.

231. Felske, J. D., Tian, C. L., "Calculation of the Emersivity of Luminous Flames", Combustion Science and Technology, Volume 7, Issue No. 1, pp. 25-31, 1973.

232. Fenimore, C. P., "Ratio of NO_2 to NO in Fuel Lean Flames", Combustion and Flame, Volume 25, Issue No. 1, pp. 85-90, 1975.

233. Fenimore, C. P., Jones, G. W., "Comparative Yields of Soot from Premixed H/C Flames", Combustion and Flame, Volume 12, Issue No. 3, pp. 196-200, June, 1968.

234. Fenimore, C. P., Jones, G. W., "Coagulation of Soot to Smoke in Hydrocarbon Flames", Combustion and Flame, Volume 13, Issue No. 3, pp. 303-310, June, 1969.

235. Feugier, A., "Effect of Metal Additives on the Amount of Soot Emitted by Premixed H/C Flames", ACS Div. Fuel Chem. Preprints, Volume 22, Issue No. 1, pp. 211-218, Feb. 1977.

236. Feugier, A., "Soot Oxidation in Laminar Hydrocarbon Flames", Combustion and Flame, Volume 19, Issue No. 2, pp. 249-256, Oct. 1972.

237. Feugier, A., "Soot Oxidation in Laminar Diffusion Flames", Heat Transfer in Flames, Adv. in Thermal Energy, pub. by Scripta Book Co., Washington, D. C., pp. 487-494.

238. Feugier, A., "Effect of Alkali Metals on the Amount of Soot Emitted by Premixed Hydrocarbon Flames", Comb. Inst. Eur. Symp., Paper #68, pp. 406-411, Sept. 1973.

239. Flagan, R. C., Galant, S., and Appleton, J., "Rate Constrained Partial Equilibrium Models for the Formation of NO from Organic Fuel Nitrogen", Combustion and Flame, Volume 22, Issue No, 3, pp. 299-311, 1974.

240. Foster, P. J., Narasimhan, K. S., "The Rate of Growth of Soot in Turbulent Flow", 10th Int. Symposium on Combustion, pp. 253-257.

241. Franceschi, A., et al., "Formation and Determination of Perinapthenyl Radical and PCAH in Combustion Processes", Comb. Sci. and Tech., Volume 14, Issue No. 1-3, pp. 33-41, 1976.

242. Franceschi, A., et al., "On the Mechanism of Soot Formation in a Vertical Flow Reaction", Comb. Sci. and Tech., Volume 14, Issue No. 1-3, pp. 57-62, 1976.

243. Fredette, P. E., "Effect of Additives on NO_x and Particulate Emission from Fuel Oil Combustion", Rensselner Poly. Inst. Thesis, University Microfilm No. 72-10, 856, 1972.

244. Gills, B. G., "Production and Emission of Solids, Sulfur Oxides, and NO_x from Liquid Fuel Flames", J. Inst. Fuels, Volume 46, Issue No. 383, pp. 71-76, 1973.

245. Gilyazetdinov, L. P., "Coagulation Growth of Soot Aerosol Particles", Adv. Aerosol Phy., Volume7, pp. 49-54, 1973.

246. Grodridge, A. M., Horsley, M. E., "Carbon Formation in Large Residual-Fuel-Oil-Fired Burners", J. Inst. Fuel, Volume 44, Issue No. 369, pp. 599-606, Nov. 1971.

247. Gouldin, F. C., "Controlling Emissions from Gas Turbines - Importance of Chemical Kinetics and Turbulent Mixing", PB 227862/OGG, p. 35, 1972.

248. Graham, S. C., Homer, J. B., "Light Scattering Measurements on Aerosols in a Shock Tube", Proc. 9th Int. Shock Tube Symp., pp. 712-719, 1973.

249. Graham, S. C., Homer,J. B. and Rosenfeld, J.L.J., "Formation and Coagulation of Soot Aerosols", Int. Shock Tube Symp. 10th Proceedings pp. 621-631, July, 1975.

250. Graham, S. C., "Refractory Indicies of Isolated and of Aggregated Soot Particles", Comb. Sci. & Tech., Volume9, Issue No. 3-4, pp. 159-163, 1974.

251. Guerrini, R., DiLorenzo, A., and Masi, S., "Chemical Characteristics of Soot Collected in An Industrial Diffusion Flame", Riv. Combustion, Volume 30, Issue No. 2, pp. 46-51, Feb. 1976.

252. Hammond, E. G., Beer, J. M., "Spacial Distribution of Spectral Radiant Energy in a Pressure Jet Oil Flame", Heat Transfer in Flame Pub., Scripta Book Co., pp. 282-291, 1974.

253. Hazard, H. R., "Conversion of Fuel Nitrogen to NO_x in a Compact Combustor", J. Eng. Power, Volume 96, Issue No. 3, pp. 185-188, 1974.

254. Hein, K., "Recent Results on the Formation and Combustion of Soot in Turbulent Fuel Oil and Gas Flames", Comb. Sci. & Tech., Volume 5, Issue No. 5, pp. 195-206, July, 1972.

255. Hill, W. E., Farrell, R. A., and Davis, L. B., "Total Flame Radiation and Two Color Flame Temperature in Industrial Gas Turbine Combustion System", *ASME Paper 76-HT-57*, Nov, 1976.

256. Hilliard, J. C., and Weinberg, F. J., "Effect of N-Containing Plasmas on Stability NO Formation and Sooting of Flames", *Nature*, Volume 259, Issue No. 5544, pp. 556-557, 1976.

257. Hinohara, T., "Carbon Streaks in Diffusion Flames and the Structure of Diffusion Flames", *Intern. Chem. Eng.*, Volume 5, Issue No. 1, pp. 175-179, Jan, 1965.

258. Hiroyasu, H., Kadota, T., "Models for Combustion and Formation of CO, NO_x, and Soot in Direct Injection Diesel Engines", *SAE Automotive Eng. Congress*, Paper No. 760129, p. 14, Feb, 1976.

259. Homann, K. H., "Carbon Formation in Premixed Flames", *NBS Spec. Pub. 357*, pp. 143-151, 1972.

260. Homann, K. H., Morgemeyer, W., and Wagner, H., "Optical Measurements on Carbon Forming Benzene-Oxygen Flame", *Comb. Inst. Eur. Symposium*, Paper #66, pp. 394-399, Sept. 1973.

261. Howarth, Foster, and Thring, "Effect of Temperatures on the Extinction of Radiation by Soot Particles", *Proceedings of the Third International Heat Transfer Conf., AIChE*, Volume 5, pp. 122-128, 1966.

262. Iverach, D., Kirov, N. Y., and Haynes, B. S., "Formation of NO in Fuel Rich Flames", *Comb. Sci. & Tech.*, Volume 8, Issue No. 4, pp. 159-164, 1973.

263. James, R. K., Edwards, D. K., "Effect of Molecular Gas Radiation on a Planer, 2-Dimensional, Turbulent-Jet Diffusion Flame", *ASME Paper 76-HT-54*, 1976.

264. Jancta, M. S., et al., "Soot and Gaseous Pollutant Formation in a Burning Fuel Spray in Relation to Pressure and Fuel-Air Ratio", *J. Inst. Fuel*, Volume 50, Issue No. 402, pp. 10-13, March, 1977.

265. Jenkins, D. R., "Proposed Mode of Action of Alkaline Earth Metals in Suppressing Soot", *Comb. Sci. & Tech.*, Volume 5, Issue No. 5, pp. 245-249, July, 1972.

266. Jensen, D. E., "Prediction of Soot Formation Rates: New Approach", *Proc. Roy Soc. London, Ser A.*, Volume 338, Issue No. 1614, pp. 375-396, 1974.

267. Jenkins, D. R., Cotton, D. H. and Friswell, N. J., "The Suppression of Soot Emission from Flames by Metal Additives", *Combustion and Flame*, Volume 17, Issue No. 1, pp. 87-98, Aug, 1971.

268. Jinno, H. K., Kunugi, M., "Kinetics of Soot Formation in a Flow System Simulating the Lower Part of a Laminar Diffusion Flame", *12th Int. Symp. on Combustion*, 1968.

269. Jones, A. R., "Estimate of the Possible Effects of Particle Agglomeration on the Emissivity of Sooty Flames", Comb. Inst. Eur. Symposium, Paper #63, pp. 376-381, Sept. 1973.

270. Jones, A. R., Schwar, M. J. R., "Light Scattering by Particles in Flames", High Temp - High Pressure, Volume 1, Issue No. 4, pp. 369-386, 1969.

271. Jones, J. M., Rosenfeld, J.L.J., "Modeling for Sooting in Diffusion Flames", Combustion and Flame, Volume 19, Issue No. 3, pp. 427-434, Dec. 1972.

272. Kadota, T., Hiroyasu, H., and Farazandehmhr, A., "Soot Formation by Combustion of A Fuel Droplet in High Pressure Gaseous Environments", Combustion and Flame, Volume 29, Issue No. 1, pp. 67-75, 1977.

273. Kato, Fujii, Jurata and Mori, "Formation and Control of NO from Fuel Nitrogen: Part 1, Experimental and Modeling Studies of Fuel NO in Premixed Flat Flames", Bull.JSME, Volume 19, Issue No. 136, pp. 1189-1196, 1976.

274. Kato, Fujii and Kurata, "Formation and Control of NO_x from Fuel Nitrogen: Part II, Formation and Decomposition of Fuel NO in Diffusion Flames", Bull. JSME, Volume 19, Issue No. 136, pp. 1197-1203, 1976.

275. Kau, C. J., Tyson, T. J.and Heap, M. P., "Study of Oxides of Nitrogen and Carbon Formation in Diesel Engines", EPA/460/3-76/008-a, Volume PB-262 712/3BE, p. 199, March, 1976.

276. Kipling, M. D., "Soots, Tars and Oils as Causes of Occupational Cancer", ACS Monogr. 173 Carcinog., pp. 315-323, 1976.

277. Kito, M., Ishimaru, M., and Sakai, T., et al., "Combustion of Carbon Particles Generated from Liquid Hydrocarbon Fuels", Combustion and Flame, Volume 17, Issue No. 3, pp. 391-397, Dec., 1971.

278. Krause, et al., "Combustion Additives for Pollution Control - A State of the Art Review", EPA-600/2-77-008a NTIS No. P.B. 264068/AS,

279. Kunitomo, T., "Mean Emissivity of a Luminous Flame (Spray Combustion of Liquid Fuel)", Heat Transfer - Jap. Res., Volume 1, Issue No. 2, pp. 57-64, April, 1972.

280. Kunitomo, T., Sato, T., "Theoretical Study on Infrared Monochromatic Absorption Coefficient of Soot Particles", Bull. JSME, Volume 14, Issue No. 67, pp. 58-67, Jan. 1971.

281. Kunitomo, T., Kodama, K., "Radiation from Luminous Flames at High Pressures", Bull, JSME, Volume 17, Issue No. 113, pp. 1486-1493, Nov. 1974.

282. Kunitomo, T., "Luminous Flame Emission Under Pressure to 20 Atm.", Heat Transfer in Flames Pub - Scripta Book Co., Wash. D. C., pp. 271-281, 1974.

283. Lahaye, J., Prado, G., "Formation of Carbon Particles from a Gas Phase: Nucleation Phenomenon", Water Air Soil Pollut., Volume 3, Issue No. 4, pp. 473-481, Dec. 1974.

284. Leckner, B. O., "Elements of Radiative Heat Transfer Calculations in Flames and Gases", Arch. Procesow Spalania, Volume 4, Issue No. 4, pp. 387-398, 1973.

285. Lestar, T. W., Wittig, S.L.K., "Particle Growth and Concentration Measurements in Sooting Flames", 10th Int. Shock Tube Symp., pp. 632-639, July, 1975.

286. Liebert, Hibbard., "Spectral Emittance of Soot", NASA TN D-5647, 1970.

287. Lilienfeld, P., Anderson, D. P., and Cooper, D., "Design, Development and Demonstration of a Fine Particulate Measuring Device", EPA-600/2-77-077, April, 1977.

288. Long, R., "Polycyclic Aromatic Hydrocarbons in Flames", PB No. 2201S1/5 p. 196, 1972.

289. Long, R., Crittenden, B. D., "Formation of Polycyclic Aromatics in Rich Premixed Acetylene and Ethylene Flames", Combustion and Flame, Volume 20, Issue No. 3, pp. 359-368, June, 1973.

290. Long, R., Dearden, P., "Soot Formation in C_2H_4 and C_3H_8 Flames", J. Appl. Chem., Volume 18, Issue No. 8, August, 1968.

291. Long, R., Tompkins, E. E., "Formation of Polycyclic Aromatic Hydrocarbon in Premixed Flames", Nature, Volume 213, Issue No. 5080, pp. 1011-1012, March, 1967.

292. Lowas, T. M., Newall, A. J., "Emissives of Flame Soot Dispersions", Combustion and Flame, Volume 16, Issue No. 2, pp. 191-194, April, 1971.

293. MacFarlane, J. J., "Carbon Formation in Premixed Methane-Oxygen Flames Under Constant-Volume Conditions", Combustion and Flame, Volume 14, Issue No. 1, pp. 62-72, Feb., 1970.

294. MacFarlane, J. J., et al, "Carbon in Flames", J. Inst. Fuel, Volume 39, Issue No. 305, pp. 263-270, June, 1966.

295. Magnussen, B. F., "Rate of Combustion of Soot in Turbulent Flames", 13th Symposium (Int.)on Combustion, pp. 869-877, 1971.

296. Malte, P. C., Pratt, D. T., "Role of Energy-Releasing Kinetics in Nitrogen Oxide (NO_x) Formation in Fuel Lean, Jet-Stirred CO-Air Combustion", Comb. Sci. & Tech., Volume 9, Issue No. 5-6, pp. 221-231, 1974.

297. Malyshev, P. A., "Concerning the Measurement of Gas Flow Temperature in Soot Generators by Means of a Radiation Pyrometer", Heat Transfer-Sov. Res. Volume 5, Issue No. 2, pp. 90-91, March-April, 1973.

298. Malyshev, P. A., "Determination of the Output of Soot from the Material Balance of Soot Generating Process", Heat Transfer - Sov. Res. Volume 5, Issue No. 1, pp. 145-149, Jan. 1973.

299. Martin, G. B., Berkau, E. G., "An Investigation of the Conversion of Various Fuel Nitrogen Compounds to NO_x in Oil Combustion", AIChE Symposium Series, Volume 68, Issue No. 126, pp. 45-54, 1972.

300. Matsumura, Y., "Physiochemical Properties of Soot from Fuel Oil Burners and Automobile Engines", Atmos. Environ., Volume 7, Issue No. 2, pp. 219-224, 1973.

301. McLintok, I. S., "The Effect of Various Diluents on Soot Production in Laminar C_2H_4 Diffusion Flames", Combustion and Flame, Vol. No. 12, Issue No. 3, June, 1968, pp. 217-225.

302. Meier Zu Koecker, H., "Kinetics of Soot Formation Investigations into the Mechanism of Soot Formation in Hydrocarbon Diffusion Flames", Combustion Science and Technology, pp. 219-224, Volume No. 5, Issue No. 9, July, 1972.

303. Meier Zu Koecker, H., "High Pressure Combustion in Oxygen Diffusion Flames -- 6 Sooting Technics of 18 H/C in Unidimensional Combustion", Brennst-Chem, Vol. No. 49, Issue No. 7, pp. 193-198, July, 1968.

304. Millikan, R. C., "Sizes, Optical Properties and Temperatures of Soot Particles", Temperature, Its Measurement and Control in Science and Industry, Volume III, Part 2, pp. 497-507, 1962.

305. Mitchell, R. E., "NO_x Formation from Chemically Bound Nitrogen During The Combustion of Fossil Fuels", Sandia, Livermore Report #SAND-76-8227, P. 25, 1976.

306. Murray, I., and Sergeant, G. D., "The Onset of Luminosity in Propane/ Air Flames", Fuel, Volume No. 51, Issue No. 4, pp. 267-271, October, 1972.

307. Newall, A. J., and Lowes, T. M., "The Emissivities of Flame Soot Disperions", Combustion and Flame, Volume No. 16, Issue No. 2, pp. 191-194, April, 1971.

308. Norster, E. R., and LeFebvre, A. H., "Influence of Fuel Preparation and Operating Conditons on Flame Radiation in a Gas Turbine Combustor", ASME Paper 72-WA-HT-26, p. 8, November, 1972.

309. Oruma, Y., "Measurements of Droplet Size and Gas Temperature in Spray Combustion Flames", NAA Journal, Volume No. 14, Issue No. 11, pp. 1637-1639, November, 1976.

310. Park, C., Appleton, J. P., "Shock Tube Measurements of Soot Oxidation Rates at Combustion Temperatures and Pressures", 9th International Shock Tube Symposium, pp. 793-803, July, 1973.

311. Park, C., Appleton, J. P., "Shock Tube Measurements of Soot Oxidation Rates, Combustion and Flame, Volume No. 20, Issue No. 3, pp. 369-377, June, 1973.

312. Park, C., Appleton, J. P., "Shock Tube Measurements of Soot Oxidation Rates", MIT Fluid Mech. Labs. Pbl. 72-8, July, 1972.

313. Peskin, R. L., "Analytical Studies of Fuel Droplet Combustion - A Status Summary", AIT Publication 1705, Paper SP66-10, June, 1976.

314. Peskin, R. L., Raco, R. J., "Analytical Studies on Mechanisms of Fuel Oil Atomization", API Publication 1727, August, 1966.

315. Prado, G. P., Howard, J. B., "Formation of Large Ions in Sooting Flames", 172 ACS National Meeting, ACS Div. Fuel Chem. Prep., Volume No. 22, Issue No. 1, pp. 246-254, August, 1976.

316. Radcliff, S. W., Appleton, J. P., "Shock Tube Measurements of Carbon to Oxygen Atom Reactions for Incipient Soot Formation with C_2H_2, C_2H_4, and C_2H_6, MIT Fluid Mech. Lab. Report 713, April, 1971.

317. Rama, S., "A Study of the Growth Mechanism of Solid Particles Present in Smoke From Luminous Flames", Riv. Combustion, Volume No. 21, Issue No. 3, pp. 127-135, March, 1967.

318. Rosen, J. M., Gregor, R., "Jet Engine Soot Emission Measured at Altitude", J. Aircraft, Volume No. 11, Issue No. 4, pp. 243-245, April, 1974.

319. Rosenfeld, J. L. J., Homer, J. B., and Graham, S. C., "The Formation and Coagulation of Soot Aerosols Generated by the Pyrolysis of Aromatic Hydrocarbons", Proc. R. Soc. Ser. A., Volume No. 344, Issue No. 1637, pp. 259-285, June, 1975.

320. Sakai, T., Sugiyama, S., "Residual Carbon Particles Yielded by the Combustion of Atomized Heavy Oil Droplets", J. Inst. Fuel, Volume No. 43, Issue No. 355, pp. 295-300, August, 1970.

321. Sakai, T., Yamada, M., "In a Study of the Formation of Soots from the Atomized Residual Fuel Oil Flame",. Bull. Japan. Petro. Inst., Volume No. 695, 1964.

322. Sawyer, Brown, "The Formation of NO_x from Fuel Nitrogen", PB-252462, 1975.

323. Schaefer, R. W., Sawyer, R. F., "Pollutant Formation in Fuel Lean Recirculating Flows", NASA-CR-2785, p. 232, 1976.

324. Schiefer, R. B., "Combustion of Heavy Distillate Fuels in Heavy Duty Gas Turbines", Mechanical Engineering, Volume No. 93, Issue No. 7, pp. 36-42, July, 1971.

325. Schirmer, Quigg, "High Pressure Combustion Studies of Flame Radiation on Related to Hydrocarbon Structure", Phillips Petroleum Company Report No. 3952-65R, Volume No. AD-617191, May, 1965.

326. Shen, T. T., "Effects of Additives on NO_x and SO_2 Emissions from a Small Oil Burner", Rensselair Poly Inst. Thesis, University Microfilms 72-18, 282, 1975.

327. Siddall, R. G., Beer, J. M., "Radiative Heat Transfer in Flames and Combustion", ASME Paper 72-WA/HT-29, November, 1972.

328. Sjoegren, A., "Determinations of Carbon Concentrations in Flue Gases", *J. Inst. Fuel*, Volume No. 44, Issue No. 366, pp. 370-376, July, 1971.

329. Steffenson, D. M., *et al.*, "Effect of Fuel Additives Study", *PB No. 240169*, p. 54.

330. Stein, S. E., Golden, D. M., Benson, S. W., "Predictive Scheme for Thermochemical Properties of Pelycyclic Aromatic H/C (and Soot Formation in Hi-T Systems)", *172nd ACS National Meeting*,September, 1976.

331. Szargan, P., "The Kinetics of Oxidation of Carbon Black", *Chem. Tech. (Berlin)*, Volume No. 21, Issue No. 8, pp. 460-461, August, 1969.

332. Tankersley, B. C., "An Optical Technique for Determining the Equivalent Size and Concentration of Carbon Particles in H/C Flames", *Univ. Alabama Diss.*, Diss. Abstr. B, Volume #30, N 11, 5057B, May, 1970.

333. Taylor, P. B., Forster, P. J., "Total Emissivities of Luminous and Non-Luminous Flames", *Int. J. Heat/Mass Transfer*, Volume No. 12, Issue No. 9, pp. 1591-1605, 1974.

334. Tesner, P. A., "Formation of Soot From Aromatic Hydrocarbons in Diffusion Flame of Hydrocarbon Hydrogen Mixtures", *Combustion and Flame*, Volume No. 17, Issue No. 3, pp. 279-285, December, 1971.

335. Tesner, P. A., *et al.*, "Kinetics of Dispersed Carbon Formation", *Combustion and Flame*, Volume No. 17, Issue No. 2, pp. 253-260, October, 1971.

336. Toor, J. S., Boni, A. A., "Modeling Combustion Heat Transfer -- Radiative Transfer Between Surfaces With Non-Gray Gases and Soot", *Int. Heat Transfer Conference, 5th Proceedings*, Volume 1, pp. 56-60, September, 1974.

337. Turner, D. W., Andrews, R. L. Sigmund, C. W., "Influences of Combustion Modification and Fuel Nitrogen Content on NO$_x$ from Fuel Oil Combustion", *AIChE Symposium Series*, Volume No. 68, Issue No. 126, pp. 55-65, 1972.

338. Wainberg, F. J., Mayo, P. J., "On the Size, Change, and Number Rate of Formation of Carbon (Black) Particles in Flames Subjected to Electric Fields", *Prof. Rog. Soc. (London - Series A)*, Volume No. 319, Issue No. 1538, pp. 351-371, October, 1970.

339. Wersborg, B. L., Fox, L. K., Howard, J. B., "Soot Concentration and Absorption Coefficient in a Low Pressure Flame", *Combustion and Flame*, Volume No. 24, Issue No. 1, pp. 1-10, 1975.

340. Williams, A., "Combustion of Droplets of Liquid Fuels: A Review", *Combustion and Flame*, Volume No. 21, Issue No. 1, pp. 1-31, August, 1973.

341. Wittig, S. L. K., Lester, T. W., "Radical and Chemical Ion Precursers: Electric Field Effects in Soot Nucleation", ACS Div. Fuel Chem. Preprints, Volume 22, Issue 1, pp. 237-245, February, 1977.

342. Wong, W., Jones, A. R., "Direct Optical Evidence for the Presence of Sooty Agglomerates in Flames", Combustion and Flame, Volume No. 24, Issue No. 1, pp. 130-140, February, 1975.

343. Yamagishi, K., "Fuel Reforming in View of Low NO_x Combustion", J. Fuel Soc. Japan, Volume No. 55, Issue No. 585, pp. 12-21, January, 1976.

344. Zaghini, N., *et al.*, "Formation of Polycyclic Aromatic Hydrocarbons in a Vertical Flow Reactor", Combustion Science and Technology, Volume No. 5, Issue No. 5, pp. 225-236, July, 1972.