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Selected Results from Combustion Research at the Lewis Research Center

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Abstract

Combustion research at Lewis is organized to provide a balanced program responsive to national needs and the gas turbine industry. The results of this research is a technology base that assists the gas turbine engine manufacturers in developing new and improved combustion systems for advanced civil and military engines with significant improvements in performance, durability, fuel flexibility and control of exhaust emissions. Research efforts consist of fundamentals and modeling, and applied component and combustor research. This paper reports on some of the progress and results that have been achieved recently in all three research areas.

I. Introduction

The purpose of this paper is to present some recent results from combustion research programs being conducted at the Lewis Research Center. The material presented has been chosen to provide a general overview of the types of work being conducted rather than to be a complete review of all program activities.

The research activities of the Combustion Branch have been restructured to face the problems of the future. The emphasis of the work has changed both as a result of the restructuring and the development of long-term plans. A balanced program is planned whereby the particular skills and capabilities of Universities and contractors are utilized to complement in-house research programs. The restructuring has also provided more balance between fundamental and applied research than was evident in the past. In the recent past only a few activities that would qualify as fundamental research were sponsored by the Combustion Branch. Today, an extensive effort is planned involving Universities and contractors to investigate processes fundamental to both combustion and combustors. The restructed effort for the Branch now shows a balance between Fundamental Research and Modeling, Applied Component Research and Combustor Research. A similar balance will be made between research efforts being conducted in-house, by University grant and on contract.

The results and programs described in this paper have been selected to show typical efforts being conducted by Universities, contractors and in-house. In a similar manner results are presented that are typical of the three programmatic areas.

II. Long Term Plan

The long-term plan of the Combustion Branch has been also restructured by the inclusion of the fuels combustion efforts. Previously these programs were managed by the Fuels Research Branch. Now all combustion activities will be contained within the Combustion Branch and the efforts focused to meet the long term objectives. The objective of the long term plan is to provide a technology base that: (a) enables the development of improved combustion systems at substantially reduced cost and time; (b) provides significant improvement in combustor performance and life; (c) maintains combustor performance levels while achieving reduced levels of emissions and (d) leads to the development of fuel flexible combustors. Table I presents the program thrusts or emphasis in each of the areas of research activity. As can be seen, an attempt has been made not only to establish a balanced effort programmatically, but also an overall program where ideas and concepts move from fundamental study through research to a practical application and demonstration. This concept is illustrated in Fig. 1, which shows the interaction between the three research areas. Itemized below each research area are some of the types of work that is being and will be conducted. As stated previously this work will be accomplished through a combination of university grants, contracted, and in-house research. University grants will be primarily utilized in the area of combustion fundamentals and modeling. Contract and in-house research will generally be conducted for those experiments requiring more extensive test facilities than are typically available in universities.

III. Combustion Research Accomplishments

This paper presents results obtained in several ongoing experimental programs in each of the three programmatic areas. This is not intended to be a complete review, but rather to give a general impression of the types of research being pursued.

A. Combustion Fundamentals and Modeling

Recent work at Lewis and at several universities has concentrated upon the modeling of simple combustion flow fields and the presentation of the output through graphical techniques. One problem being studied involves the computation of a turbulent reacting flame and the interaction of the reacting gases within the combustor. Hopefully, such computations will provide insight into the phenomena of flashback for premixed combustor designs. Experimental work with this combustor has been conducted at the University of California/Berkeley. The combustor studied was a two-inch high, two-dimensional step combustor burning a propane-air mixture. High-speed, color schlieren motion pictures have been taken of the flame front during normal operation and during transition to flashback. Figure 2 is a comparison of the computed flow field with a frame taken from the color schlieren movie. Although it is difficult to judge in detail, there are many similarities between the two cases presented, particularly in the size and motion of the large turbulent eddies. Figure 3 is an example of the flow computational results. The upper figure shows the flow field consisting of numerous vortex "blobs". The tail on each dotted "blob" represents the velocity vector of each blob. The flame front is represented by the dashed line; note the pockets of combusting gases in the downstream region. The lower figure is a frame with color representation of the temperatures of the flow field depicted in the upper figure. Upon careful study of movies made from frames like those shown in Figs. 2 and 3, one gains a better insight into the flow and an improved ability to model it correctly.

In order to understand what was happening and to predict the phenomena, the essentials of the physics were put into the mathematical statement of the problem. These include: (1) the randomness of the turbulent phenomena, (2) the vorticity in the shear layer, (3) the volume expansion of the reacting gas, and (4) the molecular motion of the flame as given by the laminar flame speed.

A numerical technique for the analysis of turbulent flow associated with combustion was used. The technique utilized Chorin's RVM (Random Vortex Method), an algorithm capable of tracing the action of elementary turbulent eddies and their cumulative effects without imposing any restriction upon their motion.[1] Introduced was a flame propagation algorithm, also developed by Chorin, in conjunction with volume sources modeling the mechanical effects of the exothermic process of combustion. We wanted to predict the large scale structure, the eddy shedding frequency, and the motion of the flame layer.

Computer produced movies of the instantaneous velocity vector field and color coded volume fraction burned were used to observe the simulation. The solution for reacting flow "mimicked" quite satisfactorily the essential features of turbulent combustion in a lean propane-air mixture that were observed in the laboratory by means of high speed schlieren cinematography. By observing the phenomena on movie film the time dimension is easily appreciated in the solution. Numerical experiments can now be performed to determine what happens in the flow. New interactions and phenomena can be observed.

By putting in the essential ingredients, we have gone far in understanding the interaction of simultaneous phenomena. The observance of the interaction leads to its understanding and finally to its control.

Another attempt to model combustor flows is being done at the University of Oklahoma.[2] There attempts are being made to predict the swirling flow fields that are found in axisymmetric combustor geometries. As before, the work consists of experimental work and computational efforts. The accuracy of currently available prediction codes for swirling recirculating confined flows is in doubt because of questionable turbulence models and the lack of an experimental data base. Suitable turbulence models must be developed as a prerequisite for prediction of the more complex turbulent reacting flow field. Experimental studies include measurement of streamline patterns, time-mean velocities and turbulence in a confined swirling recirculating flow field. Flow visualization is being used to observe the effect of various geometry parameters on the flow streamlines. Turbulence data are being obtained with hot-wire anemometers.

Computational efforts consist of a development of a two-dimensional axisymmetric swirl flow code based upon the TEACH program. As turbulence models are deduced from the experimental efforts, they will be incorporated into the program. The ability of the revised program will be validated by comparison with experimental results. Some preliminary results of both efforts are shown in Fig. 4. This figure compares calculated streamlines with those shown by flow visualization for an axisymmetric combustor with and without swirl. Without swirl the flow attaches to the wall at about two can diameters. With swirl, two recirculation zones are established, one on the outer diameter near the headplate and the other being a large zone located on the axis. These streamlines are confirmed by the flow visualization studies shown at the right.

Other areas of fundamental combustion research are concerned with the atomization and vaporization of fuels, chemistry of combustion including the modeling of pollutant formation processes, and the dynamics of flows in combustion.

B. Applied Component Research

A considerable portion of the in-house research work is devoted to Applied Component Research. Many programs are being conducted on fuel injection, advanced combustor liners, mixing of dilution jets, and determining the effects of alternative fuels.

Fuel injection. Several recent efforts in the area of fuel injection are presented here. At Lewis we have a continuing effort to extend the knowledge on the formation of sprays. The use of laser diagnostic tools has greatly facilitated this effort over the techniques used in the past. The most recent work is illustrated in Fig. 5. This composite figure summarizes that work. A schematic diagram of the test facility is shown at the top left. Air, drawn from the laboratory supply system, is fed into a long plenum chamber. Fuel injectors are mounted at the end of the chamber, spraying into the ambient air. A scanning radiometer is positioned to survey the spray just downstream of the pipe exit. The details of the scanning radiometer are shown in the top right figure. The radiometer consists of a one-milliwatt Helium-Neon laser, a lens system, a scanner (light-chopper) and a photomultiplier detector. With this system, it is possible to quickly and accurately determine the mean spray drop diameter from the amplitude and width of the scattered light beam. Present studies using this system have concentrated on determining the parameters affecting the formation of sprays from single holes with injection across the airstream. By obtaining spray data over a wide range of fuel and air flows, correlations have been developed and extended for such sprays. This correlation is presented in the lower left figure. The ratio of the injector diameter to the mean drop diameter is correlated with the product of the Weber and Reynolds numbers. The Weber number is the ratio of the aerodynamic airstream force to the liquid surface tension force, and the Reynolds number is the ratio of the hydrodynamic to viscous forces of the liquid jet. Two correlations are shown; one for capillary wave breakup and the other for acceleration wave breakup. Capillary wave breakup of liquid jets occurs when the Weber number is low, the liquid jet wavelength is relatively long and the ratio of the orifice diameter to the critical wavelength is also low. Drops of relatively large sizes are formed under these conditions. When Weber numbers are high, the liquid instability wavelength is short, and the ratio of orifice diameter to critical wavelength high, then the atomization is predominately by an acceleration wave type of breakup.[3] As indicated by the change in slope of the correlation shown in the figure, the transition from capillary wave to acceleration wave breakup occurs at a value of the Weber number-Reynolds number product of 10^6. Correlations such as this are useful in predicting injector performance over wide ranges of operating conditions and provide a basis for future studies to investigate the effects of air swirl and fuel injector design features.

Another study related to fuel injection is shown in Fig. 6. In this study a laser drop size measuring instrument was used to determine the effect of a mixing venturi added to a fuel injector-swirler combination. The top left figure shows an exploded view of the three components; the mixing venturi, the fuel injector, and the air swirler. The top right photograph shows the Malvern spray analyzer used in this experiment along with its associated peripheral equipment. Prior to the spray size measurements, combustion tests using the mixing venturi had been performed.[4] Those tests showed that the use of the venturi yielded significantly lower NO_x emissions. The swirler, fuel injector, and venturi were set up for measurement of spray drop size using water instead of fuel. Typical results at an air swirler pressure drop of three percent are shown in the bottom figure. Over the liquid flow range tested the venturi was responsible for a considerable reduction in the mean drop size of the spray. Figure 7 compares the NO_x emission results obtained with and without the mixing venturi as a function of the combustor equivalence ratio. The measured NO_x emission index values have been divided by computed value of the fuel spray Sauter Mean diameter, squared. The computed values of fuel spray drop diameter were estimated from the values obtained by the Malvern instrument and the accepted correlations relating spray drop size to liquid property and nozzle parameters. The results fall basically on one line, which indicates that the effect of the venturi in reducing NO_x emissions was primarily by the reduction in fuel spray drop size. Similar results, correlating emissions to the square of the Sauter Mean Diameter have been found in an earlier unrelated study for a variety of air blast fuel injector modules.[5] This study indicates that mixing venturis installed downstream of fuel injector-swirlers provides a real benefit in the control of NO_x emissions.

Fuel effects on combustion. The concern over the possible widespread use of broadened property fuels has prompted many studies as to what the effects of such fuel use will be on combustors.[6] We have been studying the possible effects of broad property fuels on combustors at a variety of operating conditions with different fuels. In one study we have measured the spectral radiance of the flame in a can combustor. Radiance measurements from 1.55 to 5.5 micrometers in wavelength were recorded at three axial locations in a JT8D combustor can. Two fuels, ERBS (Experimental Referee Broadened Specification), indicated in the figure as a low hydrogen content fuel, and Jet-A, differing in volatility, viscosity, and chemical composition were burned at several combustor operating conditions. This study and the results obtained are summarized in Fig. 8 and in Ref. 7. The upper portion of the figure illustrates the test arrangement of the JT8D combustor. A scanning radiometer was arranged so that the flame could be observed through each of three viewports; one each in the combustor primary, secondary, and tertiary zones. The results of the study are summarized in the three bar charts at the bottom of the figure. The first chart shows an analysis of the radiative components and the contribution of each to the total measured radiant energy. These data are for ERBS fuel at an overall fuel-air ratio of 0.0155 as measured at the secondary zone location. The greatest contributor to radiation was found to be soot, followed by carbon dioxide, and water vapor at significantly lower levels. The liner wall, opposite the viewing port, contributes only slightly to the total radiant energy. The second bar chart compares measured levels of radiant energy at each location for each fuel tested, again at 0.0155 fuel-air ratio. At each location the radiant energy levels are higher with the ERBS fuel than with Jet-A fuel as one would expect from the lower percent hydrogen of ERBS fuel. The last bar chart is a comparison of the estimated flame temperatures at each zone for the two fuels. The ERBS fuel shows significantly higher flame temperatures than Jet-A in the secondary and tertiary zones. This is indicative of continued droplet burning with the less volatile ERBS fuel in the downstream portions of the combustor. The radiometer sees these burning drops and the associated high temperature soot particles and as a result high flame temperatures are computed. From studies such as these one gains insight into the various processes within a combustor and of the effect of various operating variables including the effects of various fuel properties.

C. Combustor Research

In the area of Combustor Research a variety of new combustor concepts are being studied both on contract and in-house. In contracted research, efforts are underway in the Broad Specification Fuels Program to examine combustor concepts that can burn broadened property fuels with no loss in performance or durability.[8] Three combustor concepts are being studied by each Contractor. One concept is the baseline engine combustor, the CF6-80 and JT9D-70 combustors. The second concept studied represents a significant advance in technology and builds upon the results of the Experimental Clean Combustor Program[9] by testing advanced versions of the Double-Annular and Vorbix combustors. The most advanced concepts to be studied will be new combustor designs employing variable combustor geometry.

Another large contract effort is the Clean Catalytic Combustor Program whose purpose is to investigate several staged combustor concepts that utilize a catalytic combustor element as the main stage. Ground start and idle operation is obtained with a conventionally designed pilot stage. At higher power levels, fuel is provided to the main stage, the catalytic combustor. Combustion tests with these new combustors are just beginning.

A third contract program is the Advanced Low Emission Combustor Program.[10] In this program four combustor concepts will be studied that utilize lean-premixed, prevaporized fuel combustion as a technique to achieve very low levels of exhaust pollutants. Figure 9 illustrates the features of these combustor concepts and shows the benefits expected. The combustor sketch at the top of the figure schematically illustrates the features of these combustors. Ignition and idle operation is obtained with the pilot stage which has been optimized to produce minimum levels of idle pollutants by employing the techniques explored in the Low Power Emissions Reduction Program.[11] Such features include impingement cooling of primary zone liners, the use of heated cooling air to augment combustion, and the use of thermal barrier coatings on the liners. The main combustor stage burns a premixed, prevaporized fuel-air mixture. Fuel is injected upstream and is vaporized and mixed with air as it passes down the premix passage. A flameholder, located at the end of the premix passage provides the required stabilization region for the main combustion zone. The expected benefits of this approach are improved performance, reduced emissions, increased hot section durability, and fuel flexibility. The benefits are graphically illustrated in the charts at the bottom of the figure. Since premixing tends to provide a uniform fuel-air ratio profile, a significant reduction in exit temperature profile hot spots is expected as well as a general reduction in the exit temperature pattern factor. These effects are illustrated in the first graph. The next graph illustrates the predicted level of emissions of CO and NO_x for these LPP combustors as compared to the emission levels of current combustors. Significant reductions in both emissions are predicted. The third figure compares the relative liner life for current combustors with that estimated for lean premixed, prevaporized combustors burning Jet-A or future broad property fuel. For current combustors a 20 percent, minimum, life reduction has been estimated with the use of broad property fuel. Since LPP combustors operate fuel lean and with uniform combustion a 50 percent life gain has been estimated when Jet-A fuel is used. Some decrement in liner life is expected with the use of broad property fuel, but due to the unique character of premixed combustion there should be a significant life gain when compared to the anticipated liner lifetimes of more conventional combustors.

Swirl-flow combustor. An in-house combustor program is investigating the effect of full-rotational swirl on combustion and emissions of a large annular combustor. Figure 10 summarizes the features of this program. A cross-sectional sketch of the combustor is shown at the upper right of the figure. The combustor consists of large annular pilot zone on the outside of the swirl-flow main zone. The swirl vanes are indicated by the cross-hatched area. Swirl vane angles of 0, 25, 35, and 45 degrees will be investigated. Fuel will be injected either into the flow passage just downstream of the swirl vanes or from the end of the centerbody dividing the pilot zone from main zone. As designed, approximately 60 percent of the airflow passes through the main zone. The photograph at the top left of the figure is a view looking into the combustor with the inner liner removed. The swirlers and fuel nozzles of the pilot zone can be seen as well as the main zone flow passage inboard of the pilot. High velocity swirl flow offers several potential advantages for combustion systems. It was found by George Lewis[12,13] that the effect of large imposed g-forces was to increase the flame speed of premixed fuel-air mixtures. The graph at the lower left shows the relative increase in flame speed as a function of the imposed g-field. Roughly, a four-fold increase in flame speed is possible at g-field levels up to 4000 g's. The points on the curve represent the various g-levels that will be obtained by varying the swirl angle imparted to the flow. Several benefits are expected from this novel approach. First, the increase in main zone flame speed should result in high combustion efficiencies at the very lean operating conditions required to obtain low emissions. The swirl flow should also promote rapid mixing which should result in significant improvement in circumferential exit temperature profiles. Only preliminary results have been obtained to date but they support the overall validity of the design concept. Idle emissions from the pilot stage are very low with combustion efficiencies over 98 percent. Tests with the main stage fueled have confirmed the improved uniformity of the exit temperature portion that was predicted.

IV. Concluding Remarks

This paper has presented a brief description of some selected results from the combustor research work being conducted at the NASA Lewis Research Center. This was intended to provide the reader an overview of typical work being conducted and is not a complete review of the entire effort of the Combustion Branch. Recent efforts in combustor modeling now permit us to compute and study the effect of large vortex structures in premixed turbulent flames. From such efforts we are progressing in the prediction of combustor flows and the effects of combustor geometry on the flow field. Other efforts have provided insight into the mechanism of the formation of fuel sprays and how modifications of the basic swirler-injector system can produce finer drop sizes and lower NO_x emissions. Combustor research efforts are devoted to the study of unique concepts that have the potential for reduced emissions and pattern factor while maintaining existing performance levels with both conventional and alternative fuels. Swirl-flow, catalytic combustion and lean-premixed combustors are being evaluated.

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TABLE I. - PROGRAM THRUSTS

Combustion Fundamental and Modeling

Achieve a basic understanding of the fundamental aerodynamic and chemical processes which govern combustion and analytically characterize the governing physical phenomena. Improve and validate analytic codes and models for predicting combustor internal aerothermodynamic performance and combustor exit conditions.

Applied Component Research

Evaluate new approaches for fuel injection, fuel-air preparation, liner cooling, primary zone stoichiometry control and determine the impact of broadened property fuel upon combustor components.

Combustor Technology

Investigate and evaluate the feasibility and potential benefits of new combustor concepts with the capability to maintain established performance levels using existing and broadened property fuels.

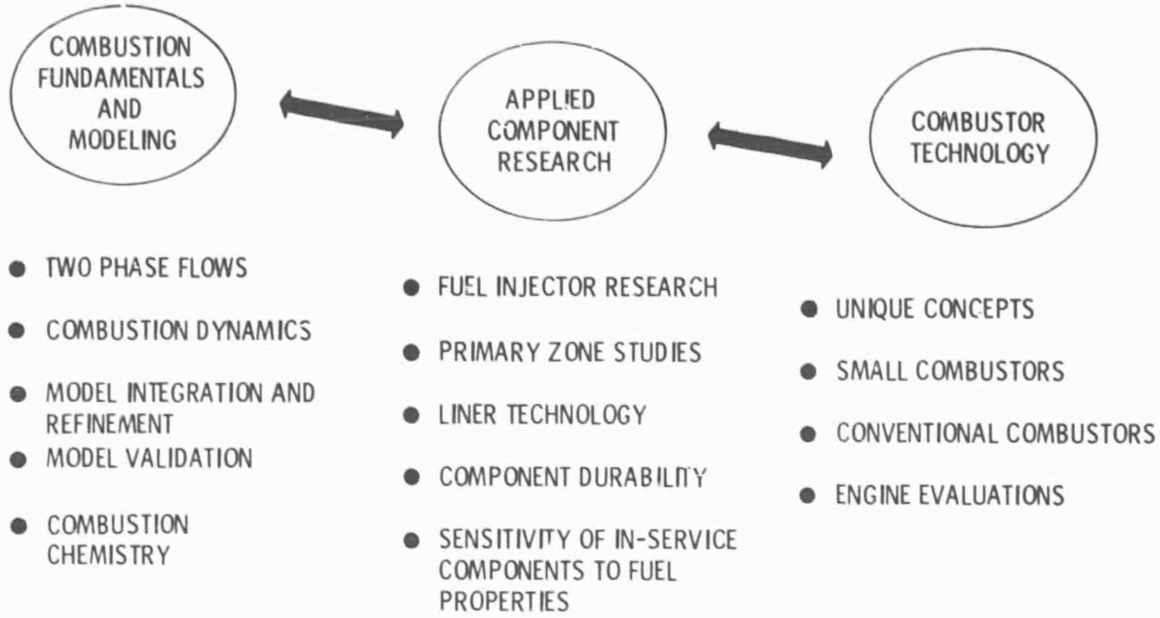

Figure 1. - Combustion Branch Research Areas.

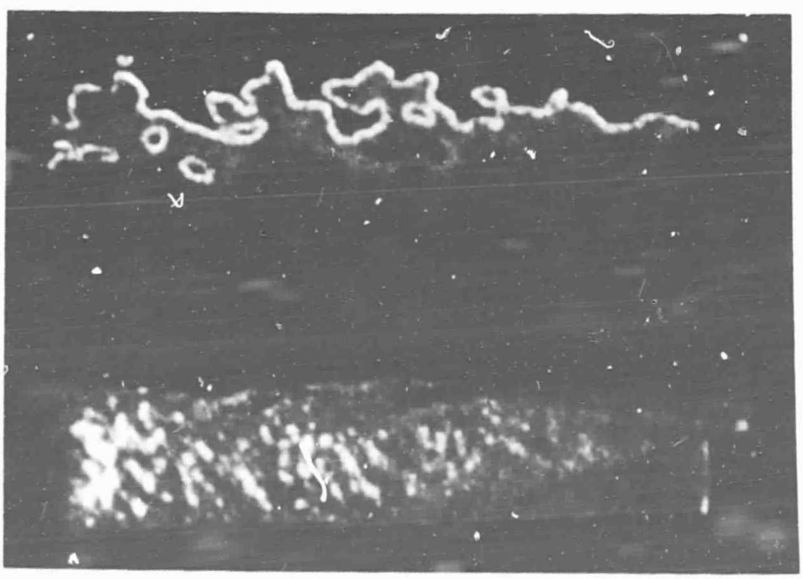

Figure 2. - Comparison of computed flow with combustion experiment.

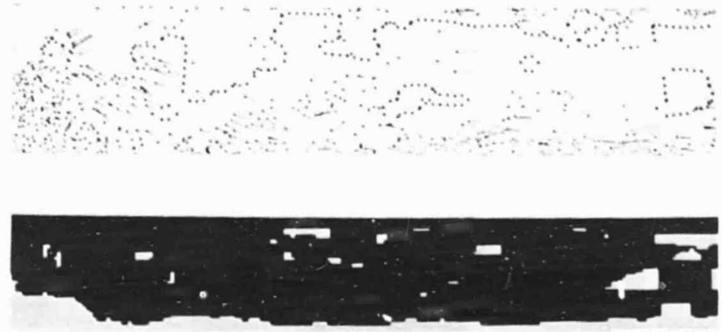

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Figure 3. - Numerical computation of flow fields and generated color movie.

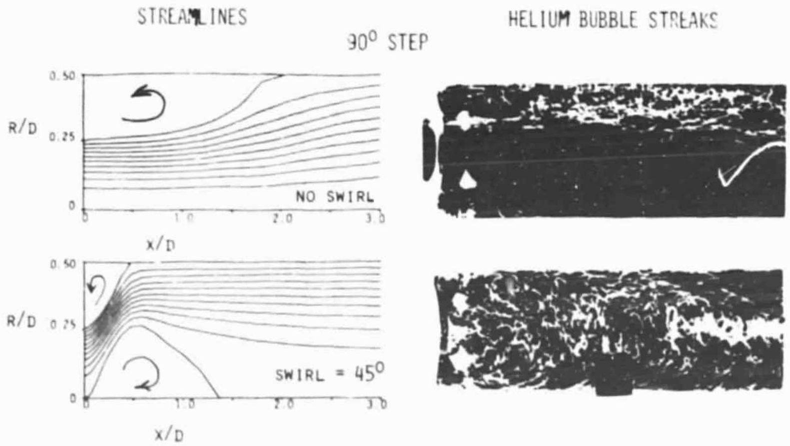
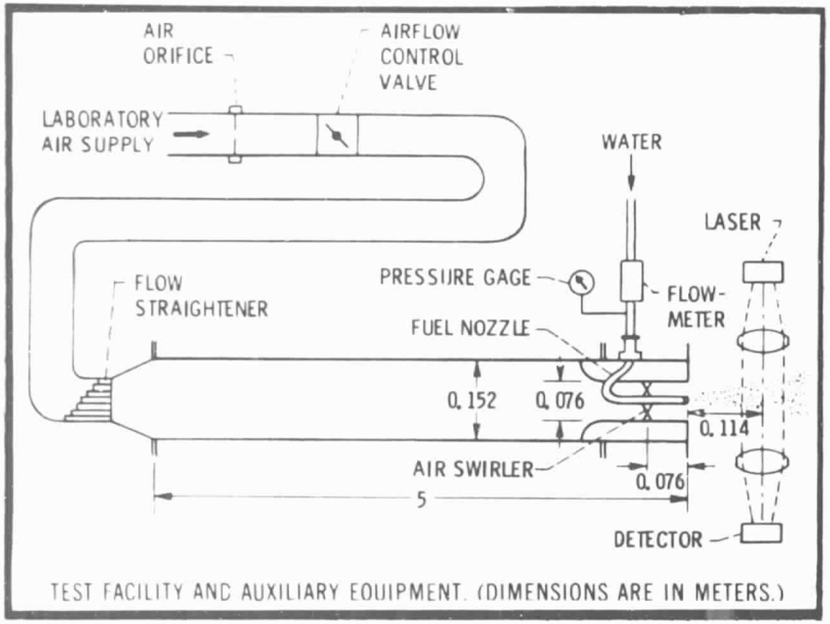
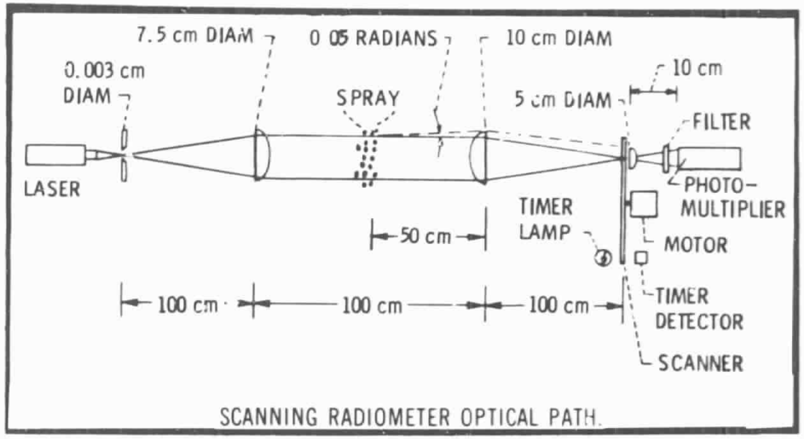
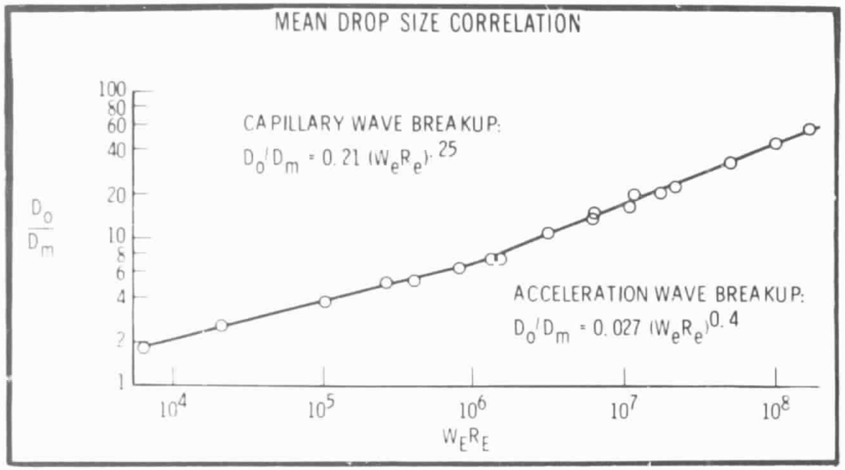


Figure 4. - Comparison between experiment and computations.







BENEFIT:

PREDICTS FUEL NOZZLE PERFORMANCE OVER WIDE RANGES OF AIR FLOW CONDITIONS.

PROVIDES BASIS FOR STUDY TO INTEGRATE AIRSWIRLER AND FUEL INJECTOR DESIGNS FOR HIGH PRESSURE COMBUSTOR APPLICATIONS.

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Figure 5. - Fuel spray formation research.

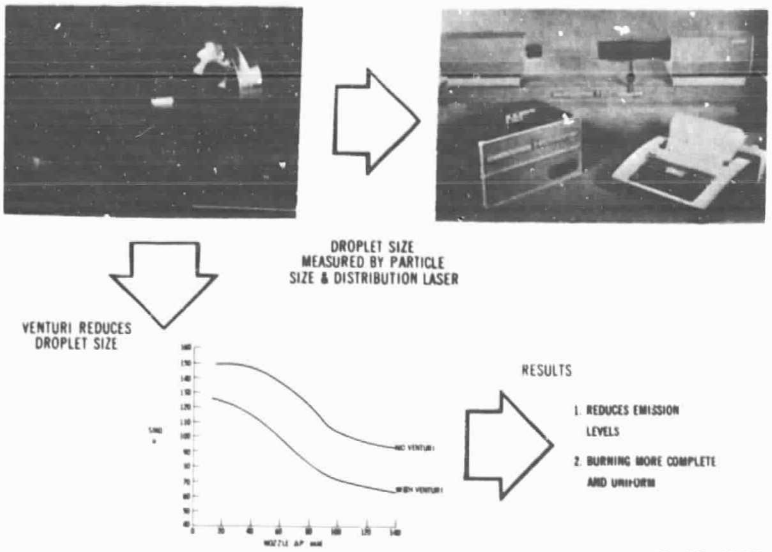

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Figure 6. - Effect of Venturi on fuel spray drop size.

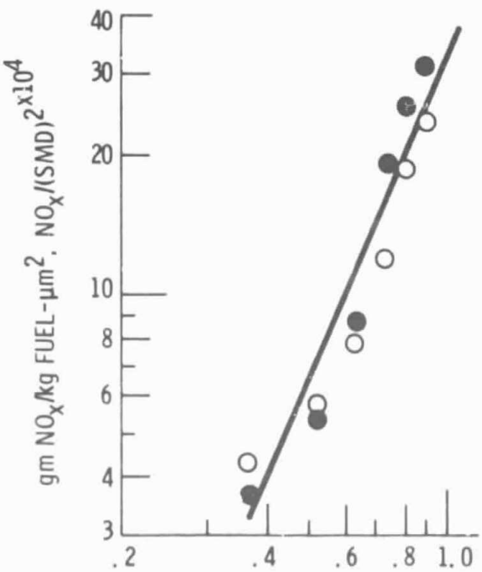

Figure 7. - Correlation of NO_x emissions and computed spray droplet SMD with burner equivalence ratio.

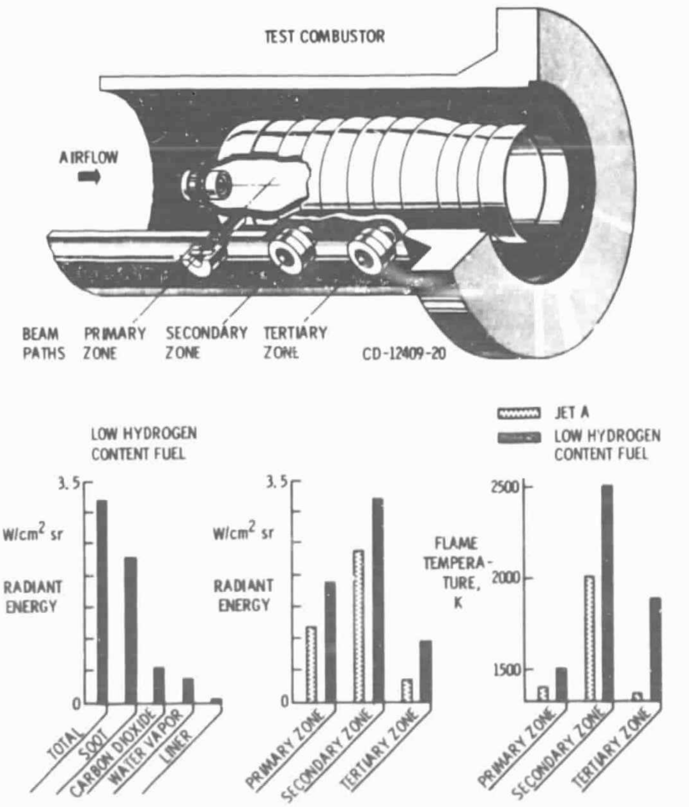

Figure 8. - Effect of fuel type on flame radiation.

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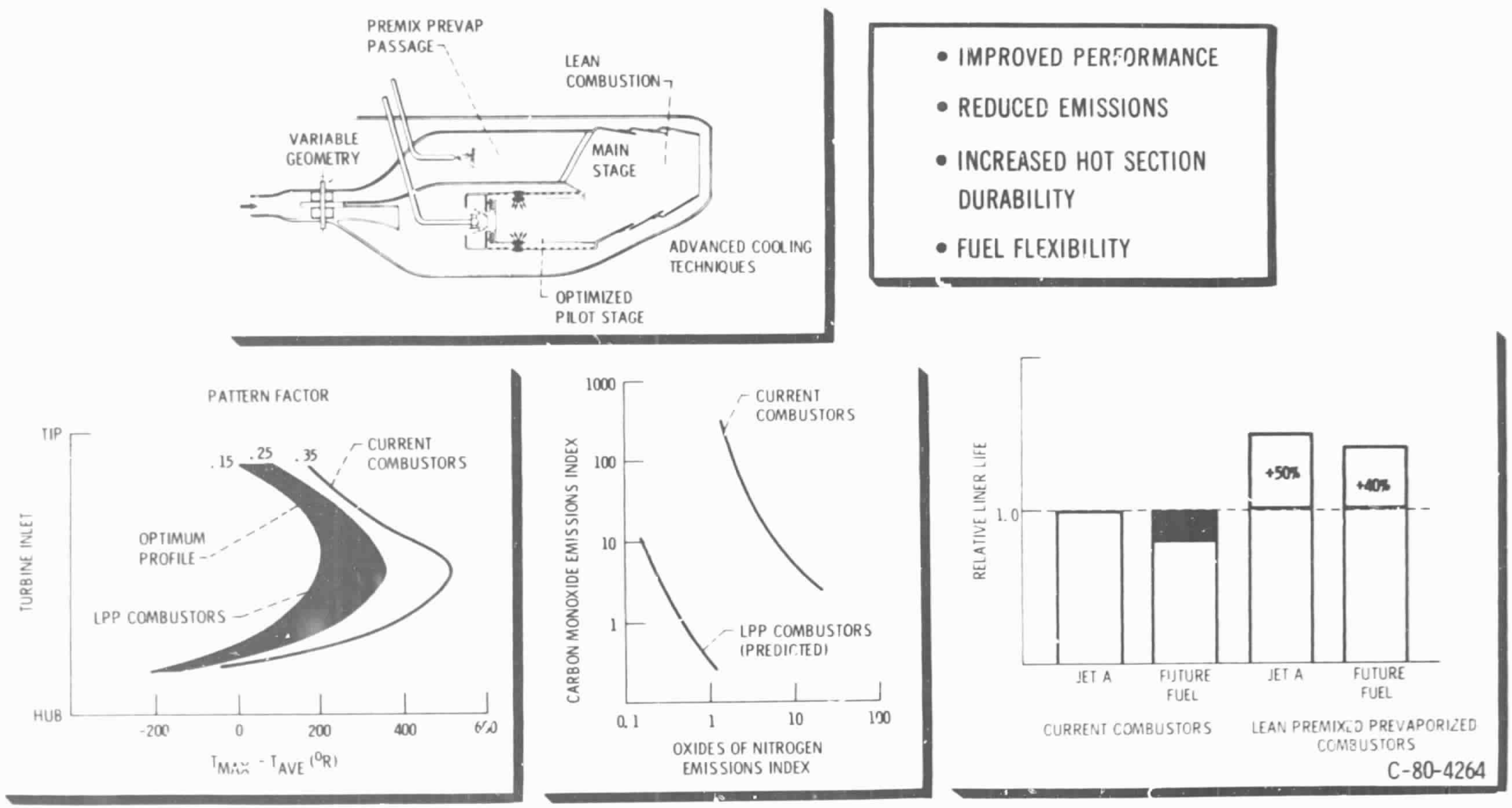

Figure 9. - The advanced low emission combustor program.

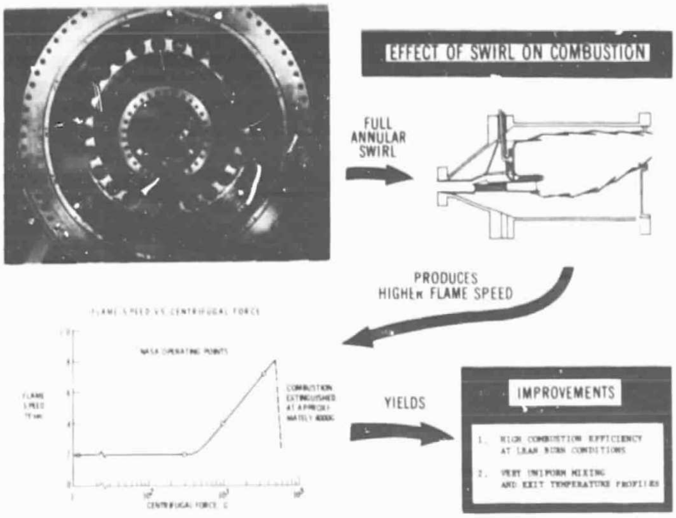

Figure 10. - Effect of swirl on combustion.

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