Air Force Basic Research for Airbreathing Propulsion

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ABSTRACT

The Air Force Office of Scientific Research provides financial support for basic research efforts in airbreathing propulsion. This support is divided among three subject areas: structural materials, combustion, and internal fluid mechanics. Summaries are given in each of those areas to address recent accomplishments which are candidates for transition to applied research and advanced technology. Future needs and opportunities for basic research also will be discussed.

INTRODUCTION - THE TECHNOLOGICAL CHALLENGE

Airbreathing propulsion is and will continue to be essential to the Air Force for the fulfillment of its mission. Requirements exist for flight Mach numbers extending from the low subsonic regime up to hypersonic values approaching the escape velocity needed for achieving low earth orbit in space.

For each new generation of propulsion systems the design engineer must address higher figures of merit. Many such measures of merit are traditional: system performance, including thrust/weight and specific fuel consumption; durability; ease of maintenance; and cost. In future system designs these requirements will be supplemented by additional needs:

1. Thermal requirements. Figure 1 shows the upward trend of turbine inlet temperatures. Higher combustion temperatures bring substantial gains in thermodynamic efficiency, particularly if active cooling of hot section components is minimized. This goal serves as the motivation for research into heat transfer, nonmetallic composite materials, and improved thermal barrier coatings. An additional thermal requirement is for the use of fuels as heat sinks for aerospace vehicles. Figure 2 reflects the growth in heat generation in Air Force fighter aircraft. Ram air not only has insufficient cooling capacity, but also may contribute to heat generation at high speeds. For this reason there is a new emphasis on the heat transfer characteristics and thermal stability of future fuels, in addition to their combustion behavior.

2. Signature reduction. Stealthy aircraft must possess more than a minimal radar scattering profile. Detection based on thermal emissions and exhaust particulates also must be minimized. Control of thermal radiation, as well as soot formation and growth, is needed to meet this requirement.

3. Combined cycles. Future aerospace vehicles and weapon systems will be designed to take off from the ground and to reach hypersonic flight speeds. Combined cycles will be needed to provide the necessary low speed and high speed propulsion. Transitions from gas turbine combustion to ramjets and/or scramjets must be addressed.

STRUCTURES

Future systems, most notably in the aerospace arena, are placing unprecedented demands on materials and structures. Performance requirements for emerging and projected aerospace structures and engines, such as sustained operating temperatures and temperature gradients, structural-to-gross weight ratios, engine thrust-to-weight ratios, enhanced operating life, and stricter safety criteria, have, in many cases, virtually eliminated from consideration most conventional monolithic materials. Figure 3, for example, shows the expected temperature distribution for sustained performance over
the hypersonic vehicle, while Figure 4 contrasts the structural-to-gross weight ratios of existing systems, including the Space Shuttle, to those of various conceptual designs for the hypersonic vehicle. The long-term research and development emphasis for meeting such needs has thus shifted to such emerging materials as metal-, ceramic-, and carbon-matrix composites. At present, they appear to be the most promising for satisfying such requirements.

The approach for creating these new multiphase materials, as described by Drucker (1981), represents a radical departure from the classical practice of processing naturally occurring materials; we are now combining at the microstructural level constituents selected from a widely diversified array of sources to produce the desired macroscopic behavior. Salkind (1976) has indicated that this concept in the design of materials represents the revolutionary impact of advanced fiber-reinforced composites.

The resulting materials are expected to be characterized by very complex structure and highly anisotropic behavior. Thus, by their very nature, these materials will not lend themselves to classical mechanics treatment. The fundamental postulate of the classical approach that the critical volume element can be made arbitrarily small, breaks down in the face of phase interactions whose influence domain is nonlocal. The basis of such microstructural feature interactions are localized, at an arbitrarily infinitesimal range. This enables the application of the concept of limit to the interior and the boundary of the material body which, in turn, makes possible the mathematical connection of the deformation (and resulting strains and stresses) of the material to a set of externally applied loads. As our materials-synthesis capabilities became more sophisticated, as they did in recent years, the range of scales over which microstructural-features evolution and interaction can be manipulated in order to influence the material's macro-behavior has expanded dramatically. The fundamental challenge of mesomechanics outlined by Haritos et al. (1987), and depicted schematically in Fig. 5, is the mathematical linking of the kinematics of such micro-feature evolutions to the macroscopic macroscopic behavior. Mesomechanics aims to evolve non-continuum mechanics for heterogeneous materials by applying mechanics principles to the microstructural constituents of multiphase materials. It requires a closer collaboration between the number of disciplines, especially those of materials science, mechanics, and chemistry. Ultimately, this approach will lead to accurate life predictions, based on the current state of damage in the material, thus improving durability, an economic issue, and reliability, a safety issue.

Traditionally, the key sciences involved in the synthesis, processing, and initial characterization of new material systems are chemistry and materials science. The mechanics community does not usually get involved until a new material has been produced and identified as a promising candidate for a range of applications. All too often, the mechanics of materials' input is not solicited until premature material failures occur. One thesis of this paper is that there is an urgent need for the mechanics community to participate in the process of new materials development at an as early as possible stage. The potential contributions to saving time and resources and to producing materials better suited for specific missions are very significant. Examples of mechanics contributions which have already been made are discussed in the ensuing paragraphs. The same time, a number of issues awaiting illumination associated with the development of novel material systems are identified, as a means of underscoring the critical need for interdisciplinary cooperation as the most efficient way for their resolution.

### Ceramics and Ceramic-Matrix Composites

Ceramics and ceramic-matrix composites have emerged as strong candidates for a wide array of high-temperature aerospace applications. Many products are already available and in use at low and moderate temperatures, such as automotive engine components, cutting tools, etc. Ceramics offer a number of advantages over metal- and polymer-based materials. They have high melting points, good strength (and, in the case of composites, good toughness), they retain most of their strength to temperatures as high as 1200°C, they are relatively light weight (good specific strength and modulus), and they will potentially cost less than most other aerospace materials. Their biggest advantage, however, lies in their environmental stability. As Prewo (1988) put it, "Polymers decompose and burn while metals corrode and melt under conditions that have little or no effect on many ceramics." Although reinforced ceramics offer a broader applications potential, understanding, describing, and predicting the behavior of monolithic ceramics is also very important; their potential high-temperature uses include bearings, heat exchangers, and low-load components. Most importantly, since they are the matrix material for ceramic-matrix composites, their behavior plays a key role in the overall composite behavior.

Research in the behavior of monolithic ceramics at low temperature has recorded good progress in the areas of identifying and describing the physical mechanisms which influence their toughness and R-curve behavior, as well as the role of microstructure and interfaces. Significant progress was achieved, for instance, by Vekinis et al. (1990), who addressed the
physical fracture processes underlying the R-curve behavior of Al2O3 ceramics. Figure 6 summarizes their findings. They directly observed, identified, and modeled three distinct crack-propagation-inhibiting mechanisms. They then quantified the contribution of each mechanism to the R-curve behavior, and made suggestions to material microstructure designers for enhanced crack growth resistance. At low temperatures, a key remaining issue is the identification and modeling of fatigue behavior of monolithic ceramics. Although investigators such as Luh et al. (1989) and Steffen et al. (1991) have been considering various aspects of cyclic crack growth behavior, it is felt that this issue is far from being resolved.

Aspects of the behavior of monolithic ceramics at high temperatures are not as well understood. While some progress has been made in understanding overall creep behavior, creep rupture, and oxidation, research is needed in the areas of fatigue, cavitation, and microstructure creep. Pagano et al. (1989) and Hutchinson (1989) provide a perspective of the state of understanding regarding these issues.

A similar situation exists in the state of understanding of the behavior of ceramic-matrix composites. That is, good progress has been achieved in identifying the mechanisms of deformation and damage at low temperatures, e.g. by Budiansky et al. (1986) and Brennan and Prewo (1982), while Schioler (1990) indicates that very little is known about their high-temperature behavior. At room temperature, additional research is needed in fatigue crack propagation. At elevated temperatures, a host of issues remain: toughness, creep, oxidation, thermo-mechanical fatigue, failure modes, role of interfaces and microstructures. It is anticipated that the physical mechanisms controlling all aspects of the materials' behavior at high temperatures will be distinct than those at work at low temperatures. Of interest is not only a description of the behavior of selected ceramic composites, but, more importantly, the understanding of the microstructure and processing connection to the macro thermo-mechanical behavior, so that in cooperation with chemists and materials scientists the mechanics community can affect improvements in the composition and processing of these materials for desired applications. Examples of progress in the mechanics of continuous-fiber reinforced ceramics have been given by Evans and Marshall (1989).

The Air Force Office of Scientific Research has identified a major new research thrust to investigate the behavior of structural ceramics and ceramic composites at very high temperatures. It is jointly funded and pursued by the basic research programs in structural durability and ceramic and nonmetallic materials. The general mechanics research goals for ceramics and ceramic-matrix composites are (1) accurate prediction of behavior and life times in service-like environments including cyclic thermomechanical loading at high average temperatures and (2) guiding the development of materials for specified performance.

**Carbon/Carbon Composites**

Carbon/carbon composites are light weight, highly refractory, exhibit superior thermal shock and creep resistance, and retain their strength to very high temperatures. Their present usage is limited to either relatively low temperatures (less than 1650°C) for extended periods of time (hundreds of hours), or to short times (tens of hours) at high temperatures. Future needs include applications at high temperatures for extended periods of time and under thermal cycling conditions. The key obstacle to satisfying these needs is the low resistance of carbon/carbon composites to oxidation. Carbon begins to oxidize at approximately 400°C. Considerable effort has been devoted over the last several years toward devising effective methods for enhancing the oxidation resistance of these materials; see, e.g. Fitzer (1987) and Stiff and Sheehan (1990). Approaches investigated for oxidation-protection systems include matrix doping with chemical inhibitors, and fiber and/or component coatings. The influence that each of these approaches will have on the thermo-mechanical properties of the resulting material system will determine the material's suitability for structural applications. It is therefore prudent that the mechanics community become involved with the chemists and material scientists working to develop oxidation-resistant carbon/carbon materials, in order to assist in guiding their efforts, by predicting the behavior of the product of each of the approaches being considered. Mechanics modeling has proven quite effective in predicting properties of both fibers and of unidirectional carbon/carbon composites, as demonstrated by Sullivan and Rosen (1990) in Fig. 7. Thus, the ultimate mechanics research goal associated with carbon/carbon materials is to develop the required analytical capability for guiding the development of oxidation protection systems for structurally useful composites. Toward this end, the senior management at the Air Force Office of Scientific Research has funded a new research thrust on Carbon/Carbon Composites, spearheaded by program managers in Chemistry, Materials Sciences, and Mechanics.

**Biomimetic Materials**

The performance/environment demands being placed on future systems point to a direction of multi-functional, adaptive materials and structures. There is already a strong movement toward that direction. We can no longer afford separate materials and components for each task. It is expected that adaptive, multifunctional components and materials will, in future systems, become the rule rather than the exception. In this possible future scenario, one has to marvel at the ability of nature to produce materials having multifunctional and adaptive systems. Early in 1990, a new research thrust, entitled "Biomimetics," was successfully advocated to
senior Air Force management by two program managers at the Air Force Office of Scientific Research. It was motivated from the realization that both inspiration and innovation can be gained in approaching the engineering of new materials by studying and imitating whenever prudent (and possible) naturally occurring materials and structures. The basic research goal of Biomimetics is to understand and describe the structure and function of naturally-evolved materials, to enable the technology goal of producing aerospace materials with superior properties by mimicking the processing and design principles mastered by nature. Examples of how nature manages to combine weak ingredients and still produce materials and structures with quite respectable properties, in this case nacre (the material of the abalone shell), are given by Currey (1980) and Sarikaya et al. (1990).

COMBUSTION

Basic research in combustion addresses deficiencies in fundamental physicochemical understanding of which prevent the designer from attaining theoretically possible, fault-free performance. The objective of Air Force basic research in airbreathing combustion is to provide a predictive design and problem solving capability. In this paper emphasis will be given to recent research accomplishments and ongoing efforts which are candidates for transitioning to design methodology. Subject areas to be discussed include turbulent combustion, sprays, measurement methods, and soot.

Turbulent Combustion

Present and near term future propulsion system design modeling capability will be based on solving averaged transport equations with closure models to account for turbulence phenomena. Such models have proven to be useful for qualitative diagnostic and design scaling studies; they are neither truly predictive nor quantitatively accurate. This assessment by Sturgess (1985) is valid today not only because of gaps in our knowledge of turbulent combustion processes, but also because of the limitations which computational hardware and software impose on the sophistication of combustor design codes.

Improved closures are needed to improve the accuracy of codes based on averaged models without imposing excessive additional demands on computational resources. Kraichnan (1989) suggested a novel mapping closure approach in which variables are mapped into functional forms which are mathematically and computationally tractable. Prof. S. B. Pope is exploring the application of this approach to combustion by comparing mapping closure predictions with numerical experiments based on direct numerical simulations. Figure 8 shows probability density function contours for the decay of an inert, passive scalar in stationary, homogeneous, isotropic turbulence predicted by Prof. Pope using a Gaussian mapping closure. The agreement between these predictions and contours calculated from a direct numerical simulation provides the motivation for further investigation of the mapping closure approach.

Computational resources needed to implement models which utilize complete knowledge of the physics and chemistry of a multiphase turbulent reacting flow system will be unavailable for the foreseeable future. For example, Baum and Rehm (1987) indicate that turbulence length scales in such flows can span four orders of magnitude. It is unreasonable to expect three dimensional, transient combustion computational capability with such grid resolution. Accordingly, research has been undertaken to reconcile the near-term future computer hardware and software with the growing understanding of combustion phenomena in order to produce the next generation of combustor design models. Examples of contributions in this area will be given in the next two paragraphs.

Vortex methods were introduced into computational fluid dynamics as means for performing grid-free Lagrangian predictions. These methods were of limited utility for combustion in that they were largely restricted to predictions of velocity behavior in constant density, two-dimensional flows. Knio and Ghoniem (1990, 1990a) and Ghoniem and Heidarinejad (1990) extended vortex methods to predictions of scalar transport in three-dimensional variable density flows. Figure 9 gives a comparison between predicted contours of vorticity and product concentration in a reacting shear layer. From these results Ghoniem and Heidarinejad (1990) suggest that product formation is proportional to vorticity rather than dissipation, as is commonly assumed in current models of turbulent combustion.

The mathematics community recently provided scientists and engineers with an exciting new approach for analyzing highly disordered phenomena: mathematical chaos and fractal analysis. It is not surprising that investigators who have been confronted with the complexity of turbulent flow eagerly sought to interpret their observations according to this new methodology. Santavicca (1990) formulated a model of flame kernel growth in which the growth rate is proportional to the ratio of the Kolmogorov to the flame kernel radius raised to the power 2/(fractal dimension). The comparison between theory and experimental data based on this formula and experimentally measured data points supports the validity of this approach. The transport processes occurring in the multiplicity of turbulent scales presumably have been represented by the single parameter representing the fractal dimension.

Sprays

The past two decades witnessed remarkable advances in the capability to model spray combustion. The state of this capability is described in several survey papers, such as Faeth (1983). Models which can account for the
turbulent combustion of dilute concentrations of droplets now can be utilized on microcomputers, allowing access to this capability to major segments of the propulsion technology community.

One of the major difficulties which remains in predictions of spray behavior is that the models which have been developed are sensitive to the initial conditions for droplet sizes and velocities. Moreover, modern compact combustors may prevent the droplet concentrations in sprays from becoming sufficiently dilute to satisfy the constraints imposed by current models. Thus, both for modeling as well as direct design purposes it is necessary to study the near-injector region of the spray, including atomization and possibly also nondilute spray behavior.

Atomization has been a daunting obstacle for spray research. Unstable liquid assumes complex geometrical shapes which are optically "thick," thus frustrating optical measurements. Faeth (1991) challenged these apparent measurement difficulties by attempting to study the atomization of a liquid jet ejected from a tube of circular cross section using holography. Faeth concluded that the spray consists of a liquid breakup region surrounded by dilute concentrations of droplets. These observations offer the hope that for certain sprays droplet interaction effects such as collisions and modification to drag and vaporization behavior can be neglected.

The experimental difficulties encountered in studies of atomization could be avoided if predictions of the resultant droplet size and velocity distributions could be predicted. Li et al. (1991) achieved some success in making such predictions based on an entropy maximization model.

**Measurement Methods**

The rapid pace of development of both lasers and computational methods for process control and data processing has revolutionized experimental research in combustion. Laser-based measurement techniques have matured to the extent that they enjoy substantial commercial success and can be found in applied technological environments, as well as in university research laboratories.

Arguably, no area of airbreathing propulsion is impacted by advances in diagnostic techniques more than hypersonics. No steady state testing capability exists, and design and development programs must be conducted in transient facilities such as shock tubes, which may provide only milliseconds of useful testing time each day. Thus the need to make time-resolved multiparameter, multidimensional measurements cannot be overemphasized. Fortunately, research initiated a decade ago is maturing to provide this capability. A conceptual view of a multiparameter, planar, laser-induced fluorescence measurement is given in Fig. 10. Hanson et al. (1988) and Hanson (1988) summarize recent advances leading up to this capability.

Droplet and spray characterization represents another area in which novel measurement techniques are contributing substantially. The sensitivity of spray combustion models to initial conditions for droplet size and velocity was noted above. Bachalo and Houser (1984) introduced phase Doppler anemometry as a means to overcome difficulties which had been encountered previously in making simultaneous measurements of droplet size and velocity. The measurement is made in the interference fringe pattern created by the passage of two laser beams in an optical arrangement similar to that of a laser velocimeter, and velocities are determined accordingly. The novelty of the size measurement is in using the phase shift created by the passage of laser rays through different chords of the droplet, thus altering the effective optical path length to an array of detectors. This approach is unlike previous approaches which were based on measurements of the intensity of scattered light, frequently leading to substantial errors.

Another method for measuring droplet size is based on Fraunhofer diffraction, as introduced by Switenbank et al. (1977). Two major difficulties were encountered in applying this method to fuel spray combustion applications: laser beam diffraction by gas-phase index of refraction gradients and multiple droplet scattering in nondilute sprays. Kenney and Hirleman (1990) derived and tested corrections to light scattering inversion operations to account for multiple scattering, while Hirleman and Dellenback (1989) designed an improved detection apparatus, shown schematically in Fig. 11, to address the index of refraction gradient problem. These two accomplishments offer the potential to utilize Fraunhofer measurements as a process control diagnostic for fuel injection in operating propulsion systems.

A new diagnostic capability allows the simultaneous measurement of both the vapor and liquid phases in an evaporating spray. Melton and Verdieck (1985) demonstrated the exciplex fluorescence technique in an oxygen-free nitrogen gas environment. The presence of oxygen currently presents difficulties because oxygen quenches the exciplex fluorescence. However, the vaporization studies which are possible in an oxygen-free environment are useful for validation of fuel spray model predictions. Melton even used the oxygen quenching itself as a diagnostic to visualize the flow patterns within droplets which are permeable to atmospheric oxygen. In addition, the ratio of exciplex fluorescence at two wavelengths was used as a thermometer sensitive to within 1 K by Murray and Melton (1985).

**Soot**

Recent research results provide significant insights into mechanisms of soot formation. These insights suggest a limited selection of
For example, by operation at high angles of attack, must also be understood. Close coupling between stages associated with the trend toward higher speed machines increases the sensitivity to inlet flow distortions. Such distortions can lead to unsteadiness and ultimately to rotating stall and surge. Hence, a significant part of our program seeks to understand the origins and effects of flow unsteadiness.

Unsteady forced response of compressor blading can delay component development by several years. Present unsteady aerodynamic models are inadequate to accurately predict the aerodynamic forcing functions required for structural dynamics analyses. Blade row forced vibrations due to unsteadiness induced by inlet distortion have traditionally been modelled in the same way as those due to the wakes of upstream blades. Recent research by Professor Fleeter and his group at Purdue University has strongly suggested that the two sources of unsteadiness are not equivalent and that current prediction methods also leave something to be desired (Fig. 14).

While the detailed sources of unsteadiness remain the subject of current and future research, quite useful models of overall compressor instabilities (rotating stall and surge) have been developed by the group led by

**Compressor Flows**

The trend in compressor flows has been and will continue to be toward higher pressure ratios from each stage. This requires higher speed machinery, and we will find lessons learned in transonic fan technology being applied to high pressure compressors, where formerly, Mach numbers were strictly subsonic. Associated with the requirement for higher speeds, swept rotor designs are becoming more prevalent to minimize shock losses. We shall require greater understanding of multistage interactions in high speed machines, both on- and off-design.

Unsteady flow behavior can affect steady state performance. The swallowing capacity of transonic, low aspect ratio compressors is affected by unsteadiness. The fluid dynamic effects of inlet flow distortions induced, for example, by operation at high angles of attack, must also be understood. Close coupling between stages associated with the trend toward higher speed machines increases the sensitivity to inlet flow distortions. Such distortions can lead to unsteadiness and ultimately to rotating stall and surge. Hence, a significant part of our program seeks to understand the origins and effects of flow unsteadiness.

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While the detailed sources of unsteadiness remain the subject of current and future research, quite useful models of overall compressor instabilities (rotating stall and surge) have been developed by the group led by
Professors Greitzer and Epstein at the MIT Gas Turbine Laboratory. This has led to current research on the control of these instabilities, with special focus on active control techniques. One concept being explored by this group, with joint support from AFOSR and ONR, is the use of moving inlet guide vanes to control incipient rotating stall which can be detected by the appearance of small amplitude azimuthal traveling waves. Preliminary work (illustrated schematically in Figure 15) has been successful in stabilizing a single stage compressor, allowing operation not only in a region much closer to the original surge line, but in a previously unstable region beyond the original surge line. The surge line itself in a controlled machine can be moved to higher stage pressures. A controlled machine is a dynamically different machine than the same machine without control. While this generic advantage of active feedback control is not generally recognized by the fluid dynamics research community, the performance benefits from active flow control are likely to be much more widely appreciated in the future.

Turbine Flows

While some of the more important research issues in compressors may relate primarily to global flow behavior, local behavior may be more important in turbine stages, especially relative to the effects of local blade heat transfer on component durability. Higher engine operating temperatures of the future and the push to higher thrust to weight ratios demand improved abilities to predict and control heat transfer in gas turbine engines. Present techniques are woefully inadequate, especially for predicting the performance of new designs. Internal cooling and film cooling techniques remain much more an art than a science, and post design research on the management of blade thermal loading by internal and film cooling flows can add years to the development time for new engines.

In FY 91 we expanded our emphasis on turbine blade heat transfer. The difficulties in predicting heat transfer are suggested by the complexity of the turbine blade flow environment depicted schematically in Fig. 16. Here, one must consider the effects of transitional flow over large portions of the blade surfaces, with severe buffeting of the boundary layer by high levels of free stream disturbances which include vortical structures and turbulence from upstream blade wakes as well as local hot spots discharged from the combustor. Compound this with rotation, curvature, pressure gradients, separation and reattachment, and compressibility.

Emphasis will be placed on the effects of spatial and temporal non-uniformities (free stream disturbances) on heat transfer, with particular attention to the sensitivity of stagnation region heat transfer to free stream disturbances. Heat transfer in regions of separation and reattachment must also be understood. Work in this area will draw more heavily on recent advances in our understanding of organized structures in transitional and turbulent flows. The receptivity of these wall bounded flows to disturbances must be understood, both from the point of view of boundary layer transition and heat transfer. With this perspective to successfully predict and manage blade heat transfer we must develop a much deeper understanding of the effects of rotation, curvature and pressure gradients on the three-dimensionality of even the base flows on blade surfaces. The interaction between thermal and aerodynamic performance must be better understood, especially for film cooling flows. In this general arena, we see significant research opportunities for those in the turbulence and transition research communities who may find the challenge of complexity more stimulating than "do-ability."

Flow three-dimensionality is a dominant issue in turbomachinery flows. Some 3-D issues, common to both turbine and compressor flows, include the highly 3-D flows in endwall regions. The role of streamwise vortices in these regions is particularly of interest. Other problems associated with highly 3-D flows include 3-D separation and its influence on heat transfer. Internal cooling flows, especially impingement cooling under the effects of rotation may also be highly three-dimensional. Because of the prevalence of three-dimensional flows in turbomachinery, we need to develop a philosophy of design in three dimensions to supplant current approaches which are basically a series of two-dimensional designs patched together.

Mixing

Understanding and controlling turbulent mixing processes is critical to the development of shorter, more efficient combustors and reduction of thermal loading on blading and exhaust nozzle surfaces. Work on turbulent mixing is carried out primarily in the Turbulence Structure and Control program and in the Airbreathing Propulsion program discussed earlier, with coordinated overlap between these programs in this area. Generally speaking, the former program does not deal with reacting flows where the reactions affect the dynamics of the flow itself. Manipulation of streamwise and azimuthal vorticity components may lead to exciting new control strategies for mixing processes. For efficient combustion it is desirable to control both the entrainment ratio and the degree and speed of molecular mixing. For thermal protection, it is desirable to limit mixing between hot mainstream flows and near wall thermal boundary layers.

Mixing in compressible flows is likely to receive increased attention, at least in the Turbulence Structure and Control program, because of the long range importance of high speed flight, and the need to assure the basic knowledge base that will be required to underpin the development of new propulsion concepts and technologies.
Computational Fluid Dynamics

Because of the high degree of three-dimensionality in turbomachinery flows, it is highly desirable to develop fully three-dimensional computational approaches that will play an increasing role in this regard, and computation of 3-D base flows is in itself a significant challenge and a likely requirement for further studies on the nature of flow instabilities in turbomachinery. Because Reynolds numbers are only moderate in this environment, there may be real hope of addressing the parametric complexity of these flows using large-eddy simulation (LES) approaches. Advances in subgrid modeling and the treatment of wall regions which are expected in our research program on Turbulence Structure and Control will be increasingly adapted and applied to turbomachinery flows in the near future. Generalization of LES approaches to include compressibility, rotation, and heat transfer will play an important role in the future.

Multidisciplinarity

It must be recognized, especially by the fluid dynamics research community, that the problems of interest are not just pure fluid dynamics problems. Fluid/structure interaction will become increasingly important as newer materials are developed for higher operating temperatures and for lighter weight engine structures. More importantly, with increased emphasis on integrated designs, future requirements will not allow blade design to proceed from fluid dynamic considerations alone. It will be necessary for fluid dynamicists to understand requirements imposed by new materials and new fabrication processes. Control and management of fluid dynamic processes in turbomachinery flows is another interdisciplinary challenge. It is not likely that control of complex phenomena can be optimized by cut and try approaches to these control problems. Formal theoretical foundations must be established.

Overall Challenges

A central challenge to fluid dynamics research in turbomachinery flows is to reduce our reliance on empiricism used to handle problems presented by parametric and geometric complexity, and by three-dimensionality and unsteadiness. The advent of new materials, and the future development of new propulsion concepts will place additional demands on our understanding and our ingenuity. Incorporating active control concepts into the design process may well have significant payoffs for the future. While the fabrication and other technologies required to make active control approaches attractive to design engineers remain to be developed, now is the time to pursue basic research on the possible benefits of such control strategies.

SUMMARY

The results and discussions which have been presented are intended to fulfill two purposes: to indicate to the research community both the direction and standards for Air Force basic research; and to provide a medium by which basic research accomplishments can be transitioned to applied technology in airbreathing propulsion. The Air Force has a strong sense of obligation to conduct basic research to meet critical technology needs. Comments and suggestions for the direction of future research activities are welcome.

REFERENCES


Figure 1. Turbine Inlet Temperature Trends

Figure 2. Heat Transfer Requirements for Fighters

Figure 3. Projected Temperature Distribution for Transatmospheric Vehicle
Figure 4. Structural-To-Gross Weight Trends Compared To Various Hypersonic Vehicle Conceptual Designs

- **CURRENT APPROACH**
  - Continuum Mechanics
  - Real Material

- **GOAL**
  - Heterogeneous Approach

  - Failure Criteria Damage-Independent
  - Unable to Predict Multiple-Failure Modes
  - Cannot Predict Interactions Among Damage Micromechanisms

**PAYOFF:** Improved Durability, Improved Materials

Figure 5. Essence of Mesomechanics: Overcome The Limitations Inherent In The Continuum Approach and Face Challenges Inherent In The Heterogeneous Medium Approach

Frictional Grain Pullout found to be the most effective toughening mechanism in monolithic ceramics

For Tougher Ceramics
- Maximize friction by increasing normal stress between grains
- Include elongated grains with high fracture strength

Figure 6. Toughening Mechanism in Al203 Ceramics
Figure 7. Micromechanics Predictions for Unidirectional Carbon/Carbon Composite Properties

Probability Density Function

Figure 8. Mapping Closure Model Predictions for Scalar Mixing Probability Density Function Evolution

Figure 9. Transport Element Model Predictions of Vorticity and Product Concentration

Figure 10. Multiparameter Planar Laser-Induced Fluorescence Measurement Schematic
Figure 11. Adaptive Method for Fraunhofer Diffraction Particle Size Measurement

Premixed Combustion

![Diagram of Premixed Combustion](http://mechanicaldesign.asmedigitalcollection.asme.org/GT/proceedings-pdf/GT1991/79023/V005T16A001/2401359/v005t16a001-91-gt-358.pdf)

T_f = 2200 K

Equivalence Ratio

Soot

No Soot

Number of C-C Bonds

Figure 12. Soot Formation Correlation for Premixed Hydrocarbon Combustion
Figure 13. Kinetic Mechanisms for Polyaromatic Soot Precursor Species Formation

Figure 14. Comparison of Blade Row Response to Wake and Inlet Distortion Forcing Functions
Compressor Instabilities
Small Amplitude Waves Provide Early Stall Warning

Co-surge
Azimuth
Rotating Stall
Flow Coefficient
Surge
Compressor
Nonuniform Inlet Flow
Moving Guide Vanes

- 25% Reduction in Mass Flow Achieved in Laboratory Single Stage Compressor
Surge line
Pressure Rise
Surge line without control
Performance Improvement
Mass Flow

Figure 15. Schematic Representation of Active Control of Rotating Stall and Surge Using Moving Inlet Guide Vanes

Figure 16. Simplified Representation of the Complex Flow Environment of Gas Turbine Blades