Florida A&M University

Excellentia Cum Canundo

FLORIDA AGRICULTURAL AND
MECHANICAL UNIVERSITY

Laboratory for Modern Fluid Physics

FINAL REPORT
NASA-FAMU University Research Center
January 1, 1992 - December 31, 1996
NAGW-2930

submitted by
Prof. Joseph A. Johnson III, Director

1800-3 East Paul Dirac Drive • Tallahassee, Florida 32310

FINAL REPORT
NASA-FAMU University Research Center

January 1, 1992 - December 31, 1996

NAGW-2930

submitted by

Prof. Joseph A. Johnson III, Director

Table of Contents

I.
Executive Summary

Our research and technology are focused on nonlinear issues in the aerothermochemistry of gases and materials and the associated physics and dynamics of interfaces. Our program is now organized to aggressively support the NASA Aeronautics Enterprise so as to: (a) develop a new generation of environmentally compatible, economic subsonic aircraft; (b) develop the technology base for an economically viable and environmentally compatible high-speed civil transport; (c) develop the technology options for new capabilities in high-performance aircraft; (d) develop hypersonic technologies for air-breathing flight; and (e) develop advanced concepts, understanding of physical phenomena, and theoretical, experimental, and computational tools for advanced aerospace systems.

The implications from our research for aeronautical and aerospace technology have been both broad and deep. For example, using advanced computational techniques, we have determined exact solutions for the Schrödinger equation in electron-molecule scattering allowing us to evaluate atmospheric models important to reentry physics. We have also found a new class of exact solutions for the Navier Stokes equations. In experimental fluid dynamics, we have found explicit evidence of turbulence modification of droplet sizes in shock tube flow with condensation. We have developed a new diagnostic tool for the direct estimation of flow velocities at MHz sampling rates in quasi-one dimensional turbulent flow. This procedure suggests an unexpected confirmation of the possibility of 'natural' closure in Reynolds stresses with deep implications for the development of turbulent models. A transient increase is observed in both the spectral energy decay rate and the degree of chaotic complexity at the interface of a shock wave and a turbulent ionized gas. Even though the gas is apparently brought to rest by the shock wave, no evidence is found either of the expected relaminarization. A unique diamond-shaped nozzle has been designed for a detailed investigation of the effect of significant streamwise vorticity on the acoustic and IR characteristics of supersonic jets. Our results provide convincing evidence of the significant effect of vorticity on the far-field noise for the diamond jet as compared to the conventional round jets. We have found that the countercurrent shear layer mixes much more efficiently than conventional coflowing shear layers. We also developed the fluid thrust vectoring procedures which use counter flow to vector a jet. Our materials research has shown that the steep stress gradients at the fiber-matrix interface could be the primary cause of interface cracks after the processing of metallic and intermetallic matrix composites. New techniques have been evolved for: the microcharacterization of materials including microplastic strain and, point by point, the misorientation and plasticity for matrix composites; thermally induced stress measurements and load relaxation; the growth and characterization of metallic matrix composite interfaces; and for the growth of ferrite materials by pulsed laser deposition.

The FAMU commitment to the HBCU Research Center also continues to be broad and deep. The Center now occupies more than 20,000ft^2 at FAMU, considerably more than the commitment in the original proposal. All of the seven new faculty lines promised in

CeNNAs related areas in physics and mechanical engineering have been provided. In addition, important new faculty appointments have been made in mathematics and in computer information systems in subdisciplines with great potential benefit to the research and education programs at CeNNAs. Beyond this, the funding machinery is being put in place to insure an appropriate level of State of Florida matching funds for the continuation of CeNNAs into the distant future.

The thoroughgoing commitment to partnerships with corporations, other universities, and NASA (as well as other governmental agencies) is confirmed by our ongoing activities. (1) All research leaders in CeNNAs are vigorously pursuing connections with NASA Research Centers. Several other governmental agencies (viz., ONR, DOE, NSF, DARPA, AFOSR and NIH) have already funded portions of our participants' research. (2) Active relationships already exist with colleagues at other universities (viz., Florida State University, Texas A&M University, The Université Nationale du Benin, Cornell University, University of Minnesota, The City College of CUNY, University of Illinois U-C). These relationships range from active scientific collaborations to research student visitations. (3) An identifiable subset of the members and prospective members of FAMU's industrial consortium have aerospace interest. Included are Honeywell Inc., Monsanto Corp., McDonnell Aircraft Company, and Control Data Corporation.

The comprehensive program of support for our students now pumps the aerospace workforce pipeline. Undergraduates are fully integrated into our research programs, making seminar presentations and co-authoring scientific papers. Our students participate in off-site research programs just as our own facilities provide enriching opportunities for students from other institutions. Our students have won national awards and have continued their careers in some of the most distinguished institutions in this country.

Therefore, the funding for five years for the NASA Center for Nonlinear and Nonequilibrium Aeroscience has produced quantitatively verifiable research achievements and quantitatively verifiable beneficial impact on the development of underrepresented minorities as professional scientists and engineers suitable as prospective NASA employees. The substantial changes in infrastructure at Florida A&M University provide advanced research instrumentation, increasingly comprehensive research implementation support services, and progressively user-friendly grants management accountability. The evidence of research productivity relevant to NASA interest is contained in the extensive CeNNAs bibliography with more than 120 entries. The evidence of substantial University commitment is contained in the high-quality facilities, the faculty appointments, and the planned initiation of a new State of Florida Institute for support of the CeNNAs activities. The thoroughgoing commitment to partnerships with corporations, other universities, and NASA (as well as other governmental agencies) is confirmed by our ongoing activities and our success in raising funds from federal, state, and industrial sources. We offer a comprehensive program for our students designed to provide both enthusiasm for advanced study as well disciplined rigorous and inspiring intellectual pursuits as energized achievers in the country's aerospace technological evolution.

2

II.
Organizational Overview

The administrative program is carried out by the Center Director as the Principal Investigator. The Director is responsible for administering the center based upon both NASA and FAMU policy as well as developing new strategies to increase the center's presence and impact. The Deputy Director manages the center operations.

In addition to an administrative staff, the center has technical input from external sources. The Technical Review Committee is comprised of NASA researchers who evaluate the center's performance yearly and provide advice aimed at making the center research as relevant as possible to the NASA mission. In addition, there is a distinguished Committee of External Visitors who provide the Center Director input on the Center's quality of performance. The committee includes two fluid dynamicists and a material scientist, each one of whom is a member of both the National Academy of Sciences and the National Academy of Engineering. The committee met twice during the five years of funding. A lists the members of the oversight committees.

The research program is organized around three major research efforts with contributions and supporting contributions from additional faculty members with overlapping scientific interests. The research areas are: advanced fluid mechanics, materials characterizations and modern fluid physics. Each research team contains faculty, post doctoral fellows graduate and undergraduate students. Table B lists the faculty contributors.

CeNNAs Structure

3
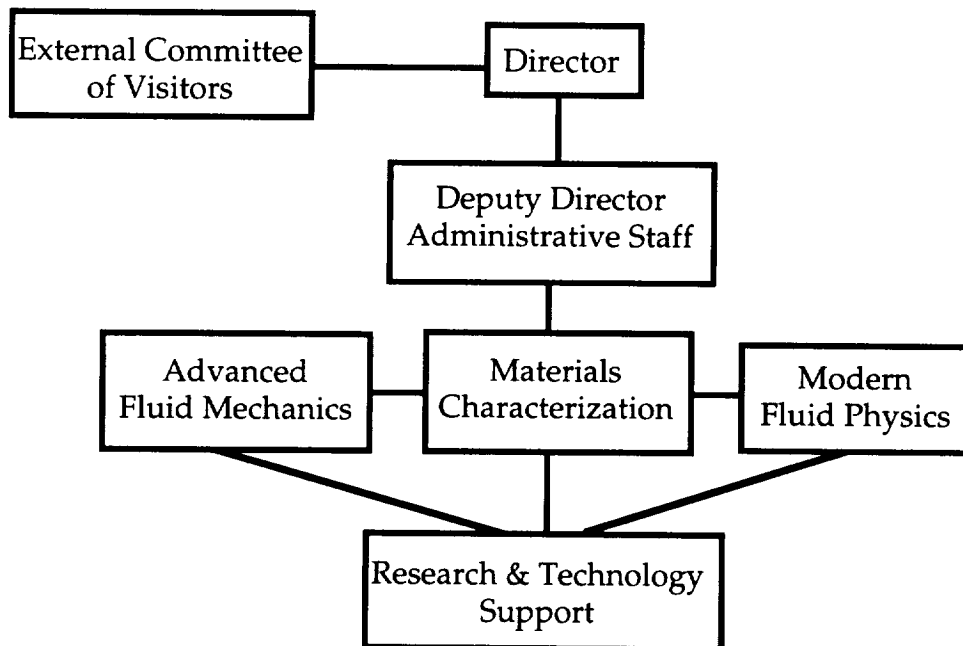
Administrative Support

Administrative Staff
Prof. Joseph A. Johnson III, Director
Dr. Lynette Edmons Johnson, Deputy Director
Ms. Delandrea Humose, Administrative Assistanat
Ms. Kimberly Reed, Secretary
Mr. Mark Bynum, Computer System Manager

Technical Review Committee
Mr. Dennis Bushnell, NASA Langley Research Cntr.
Dr. David Cooper, NASA Ames Research Cntr.
Dr. Charles Schafer, NASA Marshalll Space Flight Cntr.
Dr. Lewis Weinstein, NASA Langley Research Cntr.

External Committee of Visitors
Prof. Andreas Acrivos, The City College, CUNY
Dr. Walter Brown, AT&T Bell Laboratories
Prof. Daniel Joseph, University of Minnesota

Table A

Faculty Researchers

Prof. N. Chandra, M. E.
Prof. H. Garmestani, M. E.
Prof. J. A. Johnson III, Physics
Prof. H. Jones, Physics
Prof. R. Kennedy, Physics
Prof. A. Krothapalli, M. E.
Prof. W. Tucker, Physics
Prof. L. Van Dommelen, M. E.
Prof. C. Weatherford, Physics

Table B

III.
Research Achievements

A. Computational Atomic and Molecular Dynamics

1. Electron-Molecule Scattering

We have studied electron collisions from molecules of atmospheric interest. These include H_2, N_2, CO, O_2, CO_2 and CH_4. We have calculated integral and differential cross sections, for elastic, total, and vibrationally inelastic processes, in the energy range 0 to 20 electron volts. We have also studied energetic molecules. Cubane (C_8H_8) was first synthesized in 1964 at the University of Chicago. It has an O_h point group and a standard heat of formation of approximately 144.5 kcal/mol with a strain energy of about 166 kcal/mol. This is a strain energy of about 14 kcal/mol per carbon-carbon bond.

This research has as its central aim to study the stability of cubane and certain of its derivatives (tetranitrocubane, with four NO_2 groups, at opposite vertices of the carbon cube, and octanitrocubane, with eight NO_2 groups at each of the eight vertices of the cube). In partucular, are assessing the stability of cubanes in interaction with low-to-intermediate energy electrons (0-20 eV), with respect to certain processes that have been called electronic aging. Thus, we are determining to what extent the cubanes are subject to loss of stability when in the presence of continuum electron interactions. We are looking at the elastic and total cross sections for electron scattering in the fixed-nuclei approximation (FNA) and calculating the effective carbon-carbon vibration cross sections using body-frame close-coupling (BFCC). One of the unique features of our methods is that we solve the continuum Schroedinger equation as a partial differential equation (PDE). In this manner, we are able to consider scattering from an arbitrarily shaped atomic cluster, with numerically generated adaptive grids. As a part of the research, a new type of basis set has been employed. A wavelet basis set is being used to represent the cubanes and the new method is being merged with a coupled-cluster bound-state quantum chemistry computer program.

2. Ion-Atom Scattering

A theoretical investigation of alignment and geometrical effects in inelastic collisions of low-Rydberg atoms with rare-gas atoms and molecules is being conducted in this project. The domain of collisional processes involving excited atoms is nearly limitless in variety and complexity. The collision dynamics and the cross sections and the other observable parameters (such as correlation, polarization etc.) usually reflect details that are characteristic of a particular pair of collision partners and initial states. At low collision velocities ($v<<1$ a.u.), intermediate, near-adiabatic, quasi-molecular states that are quite system-specific

largely determine the physical development of the system during the collision. While we calculate cross sections--differential and total-and other correlation/polarization collision parameters for the purpose of direct comparisons with measurements and for applications, we give special attention to the study of the dependence of these cross sections and collision parameters on geometry (size and shape), orientation and alignment of the initial state of the target.

We are using semi-classical, close-coupling methods for all but the lowest-energy studies. The time-dependent physical quantities, e.g., transition amplitudes and electronic charge density, provide information on the evolution of the collision dynamics. Our method is the molecular orbital (MO) approach in which the total system wave function is expanded in terms of electronic MO wavefunctions, augmented by electron translation factors (ETF) to get rid of the artificial long-range couplings by satisfying the correct scattering boundary conditions. We are currently investigating systems like excited alkali atoms colliding with rare-gas atoms or closed-shell diatomic molecules (such as H_2, Li_2, N_2, etc.). This work includes investigations of charge transfer in ion-atom and ion-molecule scattering. We study charge transfer in collision of atomic hydrogen with C^{4+} at very low energies by using the molecular expansion method within the semi-classical impact parameter approach. There are some recent experimental measurements for this system. Capture into the $n=3$ states of C^{3+} atom is the main important process in this reaction. Present calculated cross sections are in close agreement with the experimental findings.

3. Molecular Integrals

Since all matter is composed of electrons and nuclei, the state of matter and its reactions are completely determined by the laws of quantum mechanics as may be expressed by the Schrodinger wave equation. However, the complexity of nature only permits approximations. The one most faithful to first principles, the one of our choice, is the *ab initio* method. This procedure leads to molecular integrals. The basis set of most fidelity is that composed of Slater-type orbitals (STOs). Currently, Gaussian-type orbitals are mostly used to avoid the computational difficulties of STOs.

Using *Mathematica,* a breakthrough in cracking the "intractable" problem of multicenter molecular integrals over Slater-type orbitals has been achieved. This problem is long-standing and a constant irritant to theoreticians in quantum chemistry and molecular physics. The complete solution of the integral problem will bring a new standard of accuracy to any calculation involving molecules or collisions of molecules with atoms or particles. (The current use of Gaussian-type orbitals will, in all likelihood, be superseded.)

B. Analytical Modeling for Complex Compressible Turbulent Flow

Motivation

Complex compressible turbulent flows are critical for a number of missions of importance to NASA. For example, turbulent boundary layers and wakes determine the forces experienced by aerospace vehicles, while combustion and mixing process also depend heavily on the complicated nonlinearities induced by turbulence. One goal in our study was to uncover the fundamental internal processes underlying turbulent flows; another to develop techniques to model those to allow computations for critical NASA applications. Still another goal was to develop numerical techniques to allow the application of massively parallel supercomputers on these problems. Such an approach was considered to be essential in order that significant progress towards more accurate computation of realistic flows becomes possible. Another goal was to develop algorithms that can deal with the complex geometries that are often encountered in true applications.

Procedures

In order to allow study of compressible turbulent flows, a massively parallel code was developed to run on the CM-2 Single Instruction/ Multiple Data (SIMD) supercomputer. Using the slicewise processing paradigm, this machine can be modelled as consisting of 2048 floating point processors in an hypercube-type architecture with distributed memory. Highly optimized complex-to-complex Fourier transforms have been developed for this machine. Since the present study required real transforms, a special distribution of the data over memory was developed that allowed the real data to be packed into complex numbers highly efficiently, and without affecting the efficiency of the Fourier transforms. The method allows matrix multiplication as an alternative incorporation of the derivatives, permitting more general problems to be handled.

Results obtained from the parallel code were used to train a feed-forward neural network using the standard back propagation algorithm. This was achieved using the Stuttgard SNNS Neural Network Software. To handle the complications induced by complex geometries, a fully mesh-free numerical method was developed based on a Dirac delta function representation of the flow field collocated with Fourier harmonic modes. Theoretical models were developed to describe the fundamental inviscid and viscous processes observed in turbulent flows. A bulk viscosity algorithm was developed to allow the accurate computation of shocklets in the flow.

Results

The implementation of the compressible turbulence code on the massively parallel CM-2 supercomputer, using the optimized slicewise Fourier transforms combined with the custom memory configuration, improved the performance of this machine significantly compared to earlier NASA work on the same machine. A processing speed of almost 1GFlop was achieved (scaled from one quarter to the full machine.) This represented optimum performance of the Fourier transforms for the used mesh sizes. No additional operations or bottle necks were introduced by the storage scheme. The number of Fourier transforms could further be held to the absolute minimum of 27 per step per point required by the compressible Navier-Stokes equations, even with conservative evaluation of the convective terms. A careful allocation of storage and selected use of reduced numerical precision further allowed the memory requirements to be kept to almost the minimum two levels required by the Runge-Kutta time-stepping scheme. This despite the fact that the compressible Navier-Stokes equations require a significant number of derivatives to be stored to avoid re-evaluation.

The neural network representation proved highly efficient in representing the behavior of the turbulent flow. The SNNS software trained easily on the data and interpolated and extrapolated them well.

Based on the turbulence computations, the mechanics of turbulence was modelled. It has been argued that the tendency of turbulence to develop alignment of the vorticity with a positive mid strain rate could be explained by assuming axially symmetric variations in pressure gradients. However, it was discovered that other, more realistic pressure distributions have the same property. These new mechanics allow the development of two-dimensional features observed in recent studies. It was observed that these developments seem closely related to the occurrence of separation in unsteady boundary layers. Since this process is now much better understood than turbulence, it open exciting new possibilities for the further study of turbulent flows.

Further understanding of the internal mechanics of turbulent flows was achieved by addressing the viscous decay. A number of important new properties of the propagation of viscously decaying rotational flows were discovered.

In order to allow computations to be performed for complex flow fields, a fully mesh free redistribution method was developed and applied on an SP-2 computer. The method, combining concepts in linear programming and functional analysis, proved extremely efficient to handle extremely complex configurations of computational points.

C. Computational Modeling of Advanced Materials and Processes

Metallic and Intermaetallic Matrix Composites (MMCs and IMCs) are considered by NASA to be the material systems of choice for use in the next generation military and civil aircraft. Fiber-matrix interfaces play a critical role in the

successful application of these composites. These composites are also characterized by the presence of high levels of thermal streses induced during the processing of MMCs. Our research efforts using analytical and experimental techniques have shown that steep stress gradients at the interface could be the cause of interface cracks after composite processing. It was shown through computational studies that processing induced residual stresses cause inelastic deformation of the matrix in certain composite systems and they also affect the fiber-matrix interface and hence the subsequent thermomechanical response of MMCs under service conditions. It was also shown that the selection of the appropriate material model for the matrix plays an important role in the predictions of the composite behavior and also rpovides scope for the optimization of the processing cycle.

A polycrystal micromechanical model for superplastic deformation has been developed. This model defines the superplastic material behavior using few material parameters which are experimentally obtained. Based on these parameters, the model could successfully predict the effect of temperature and grain size on the superplastic behavior. The microstructural changes during superplastic deformation and its mechanisms are being simulated using Monte Carlo approach. The graphical representation of the microstructural deformation process is also being developed.

Another significant contribution is in the understanding of the mechanics of interface failure process and in the evaluation of interfacial properties from fiber push-out tests. We developed a model for representing the interface behavior through minimum number of measurable parameters. Applying the model to simulate the interface failure process in push-out tests (the most widely used test for the mechanical characterization of interface) we showed that the experimental results are significantly influenced by the residual stresses. We developed a methodology using a combination of computational and experimental methods to extract interfacial shear properties from fiber push-out tests.

D. Nonlinear Phenomena in Supersonic Jets

Due to lack of detailed knowledge of mixing processes in supersonic jets very little progress has been made in the development of an effective (20 EPNdB reduction in noise with minimal thrust loss) noise suppressor that can be used in the proposed High Speed Civil Transport (HSCT). The most recent attempt is the multi-lobe mixer/ejector noise suppressor that has its origins in the work carried out during the early 1950's. In light of this, a program of research is underway to shed further light on this problem with the hope of finding an engineering solution that can help the design of a better noise suppressor. In this report, we will summarize the experimental investigations carried out to date.

1. Role of Streamwise Vorticity on Mixing and Noise Characteristics of Supersonic Jets

The need to make modern fighter aircraft 'stealthier' with reduced infrared (IR) and acoustic (noise) signatures has been the impetus behind this investigation. Recent research has suggested that the addition of streamwise vorticity, or swirling flow, enhances the mixing of the hot jet exhaust gases with the colder ambient air resulting in a reduced IR signature. In addition, the streamwise vorticity is also expected to significantly reduce the side-line noise from the supersonic jet engines, a property which may be exploited in both civil and military aircraft. Although streamwise vorticity may be introduced into the jet flow in a variety of ways by modifying the jet nozzle geometry, for a design to be practical the thrust losses due to geometric modifications must be minimal.

A unique diamond-shaped, converging-diverging (c-d), Mach 2 nozzle was designed for a detailed investigation of the effect of significant streamwise vorticity on the acoustic and IR characteristics of supersonic jets. The present diamond shaped nozzle geometry was carefully chosen for several reasons. It was expected that the sharp corners of the diamond nozzle will lead to the creation of significant streamwise vorticity and subsequently to a modification of the mixing and acoustic properties of the jet. In addition, the high nozzle area-to-perimeter ratio of the diamond nozzle leads to minimal thrust losses. The compromise in the thrust loss, together with the expected improved stealth and mixing characteristics, make the diamond nozzle an attractive choice for further exploration.

The presence of distinct 'rippled' structures along the jet periphery is clearly visible in the laser light sheet images of the jet cross-sectional plane, an example of which is shown in Fig. 1. These images, together with the results of pressure surveys conducted in the jet periphery, which display local minima and maxima (see Fig. 2), provide convincing evidence of the presence of significant streamwise vorticity in the periphery of the diamond

shaped jet. The streamwise vorticity increased the local thickness of the shear layer while only moderately influencing the jet diffusion rate. However, the effect of vorticity on the far-field noise was fairly significant; for a hot jet, a 5dB reduction in jet side-line noise was measured when compared to the noise properties of the more conventional round jets, as shown in Fig. 3.
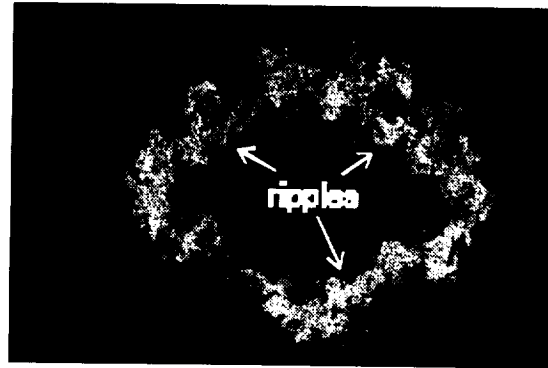

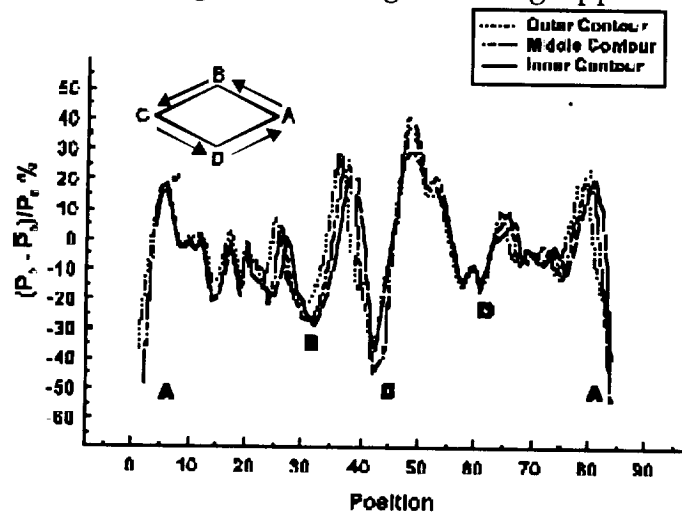Fig. 1 - Laser light sheet image showing rippled structures.

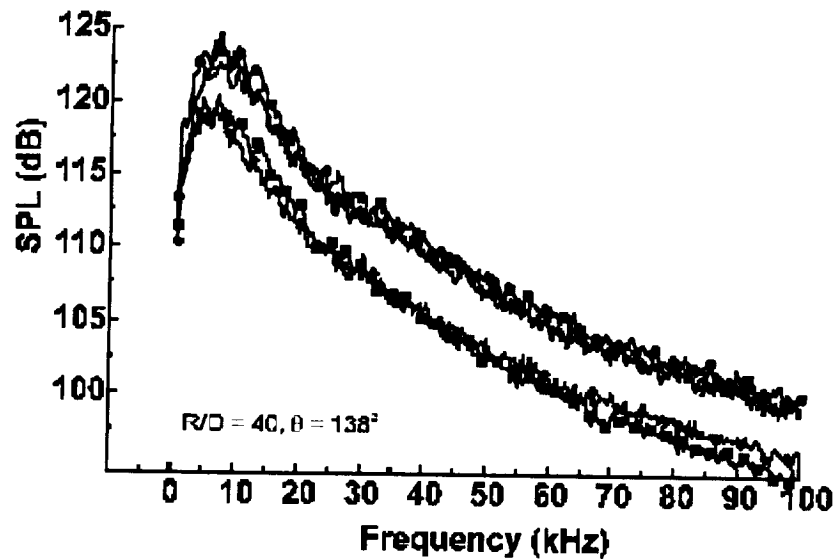Fig. 2 - Pressure surveys displaying local maxima and minima

11

Fig. 3 - Noise measurements show reduction in the overall noise levels.

The understanding gained from this investigation will be applicable in the Phase II of the NASA High Speed Research (HSR) program to optimize the design of multi-lobe ejector-suppressor systems. Experiments, in collaboration with McDonnell Douglas at Long Beach, CA, are also underway to assist in reducing subsonic jet noise as part of the NASA subsonic research initiative.

2. The Effect of Annular Counterflow on Supersonic Jet Mixing and Noise

The effect of counterflow on the aerodynamic characteristics of supersonic jets has been studied in our laboratory for several years. The counterflow technique depends on the creation of a counterflowing stream of air around the periphery of the primary jet column in the neighborhood of the nozzle exit. This is accomplished by employing a nozzle-collar configuration, where a vacuum system is used to create a secondary flow stream of magnitude U_2 in the jet near field and in a direction opposing the primary jet exhaust which is denoted by U_1. A schematic of the setup is shown in Figure 4. The creation of the secondary flow gives rise to a reduction in the jet exit plane pressure, which requires that the total pressure supplied to the jet be correspondingly reduced to maintain a nominally ideally expanded jet flow field. Experiments were conducted at a primary stream Mach number of 2 for jet stagnation temperatures between 286 K (cold jet) and 715 K (hot jet).
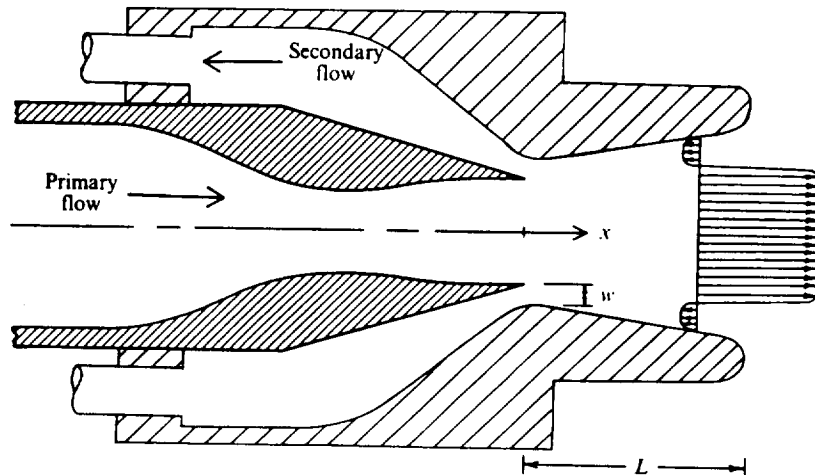
12

Figure 4. A schematic of the counterflow nozzle

The mixing characteristics of the jet were examined by conducting mean and fluctuating total pressure measurements in the axial and radial planes of the jet downstream of the nozzle-collar assembly. Fluctuating pressures measured along the geometrical axis of the jet indicate that the peak turbulence level lies closer to the jet exit when counterflow is applied (-U_2/U_1 _ 0.19). Complementary measurements made in the shear layer under similar flow conditions, indicate a significant increase in the overall turbulence level in the jet shear layers due to counterflow. These observations were essentially independent of the jet stagnation temperature. The corresponding mean total pressure measurements indicate that annular counterflow reduces the potential core length of the supersonic jets by a factor of two. Exhaustive studies conducted in our laboratory and summarized in Strykowski, Krothapalli & Jendoubi[*] attribute this mixing enhancement to increased shear layer growth rates by more than 60% compared to incompressible shear layers at similar velocity and density ratios. These aerodynamic measurements indicate that the counterflow significantly reduces the potential core, and therefore the supersonic region of the jet, and hence would appear to be an attractive control scheme for supersonic noise reduction.

To explore the possibility of noise suppression using counterflow, the far-field acoustics of the jet were examined in detail. The most surprising result of the study was that the angle between the jet axis and the peak in the Overall Sound Pressure Level (OASPL) remained fixed when counterflow was supplied, despite the rather dramatic upstream shift in the peak turbulence level in the jet. This cast doubt on the notion that the primary source of the low frequency Mach wave radiation lies near the location of the peak rms pitot pressure. However, a closer examination of the measurements as

---

[*] See the CeNNAs Bibliography, Appendix A

13

outlined in King, Krothapalli & Strykowski[**] revealed that the reduction in the convection velocity of disturbances in the jet shear layer with counterflow essentially balanced the upstream shift in source location.

Noise spectra obtained as a function of circular arc angle were used to explain why the OASPL of the counterflowing jet was higher at some angles relative to the free jet, but lower at others. In general, counterflow increases the noise levels at higher frequencies, suggesting that counterflow excites the smaller scale turbulenc, a notion that is consistent with earlier findings that the rms pressure level in the jet shear layer was increased due to counterflow. At larger angles, the counterflow caused a reduction in the sound pressure level at all frequencies. Thus, the counterflow seems to interfere with the Mach wave radiation mechanism. In summary, these measurements suggest that enhanced mixing in the region close to the nozzle exit may not necessarily result in far-field noise reduction of a supersonic jet. This is primarily due to increased turbulence production that is closely associated with the enhanced mixing processes.

3. Countercurrent Shear Layer Dynamics at Very High Compressiblity

The novel approach described above was employed at a convective Mach number, M_c, of approximately 0.82. The convective Mach number is defined as $M_c = (U_1 - U_2)/(a_1 + a_2)$ where U_1 and U_2 represent the velocity of the two fluid streams and a_1 and a_2 represent the acoustic velocity in the two fluids. Simply put, it represents the average velocity at which the large-scale structures in the shear layer are traveling relative to each flowstream; higher M_c denotes higher compressibility. The enhanced mixing of the countercurrent shear layer and the potential applications based on this enhancement prompted us to initiate the present study which further investigates the behavior and fluid dynamics of the relatively unexplored countercurrent mixing layer. Specifically, our goal was to significantly extend the convective Mach number range of the earlier study to determine whether the enhancement in mixing observed in the moderately compressible countercurrent shear layer is present in highly compressible shear layers that typically occur at realstic engine operating conditions.

A unique new facility was designed to generate a two-dimensional countercurrent shear layer with a nominal convective Mach number of 2. An extensive experimental study which addresses the mean as well as the turbulent characteristics of this flowfield was conducted. Two rectangular nozzles were used to produce Mach 2, ideally expanded jets. The nozzles are positioned in opposing directions and are mounted such that the vertical and streamwise separation between them, S and D, respectively, could be easily

---

[**] See the CeNNAs Bibliography, Appendix A

changed. The vertical separation between the between the nozzles is adjusted such that the opposing shear layers, produced by the counterflowing Mach two free jets just "graze" each other to produce a nominally two-dimensional $M_c = 2$ countercurrent mixing layer in that region. A schematic of the resulting flowfield is shown in Fig. 5; as shown in the figure, the countercurrent shear layer spans the region between the two jets. This arrangement also allows for the distance between the two jets to be varied, thus providing effective control on the amount of counterflow between the two shear layers.
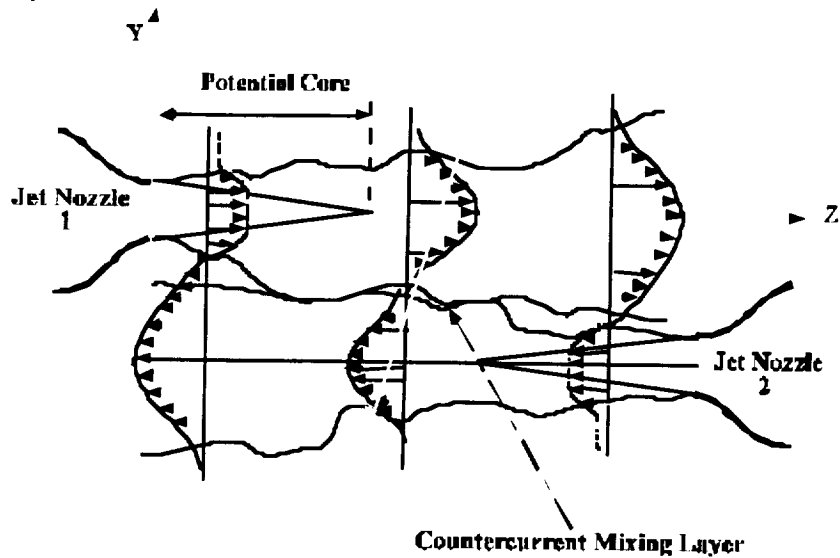

Fig. 6 - Flowfield schematic of the $M_c = 2$ countercurrent shear layer

A typical time-averaged schlieren image of the countercurrent shear layer is shown in Fig. 7. The schlieren image clearly reveals that the visual growth rate of the mixing layer with counterflow (i.e. the
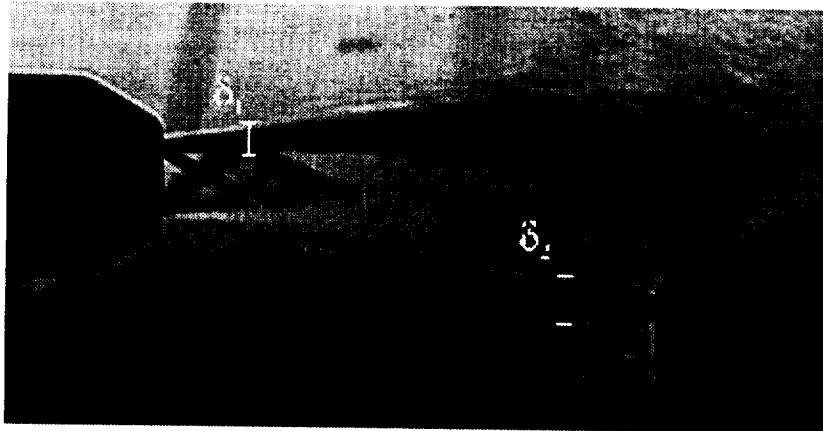

Figure 7. Time average schlieren image of a Countercurrent shear layer ($M_c = 2$)

15

mixing layer between the two jets) is significantly higher than the corresponding mixing layer without counterflow (outside mixing layer). This is easily verified by comparing the approximate widths of the upper shear layers of both jets, delineated by white lines in Fig. 7, at roughly the same distance downstream of each nozzle exit. Clearly, the upper shear layer from the lower jet, denoted by d_2, is significantly thicker, almost twice as much, than the upper shear layer from the upper jet, marked as d_1. Detailed pitot surveys were also conducted to further quantify the growth rates of the shear layer. The $M_c = 2$ countercurrent mixing layer grows at almost *twice the rate* of the upper free shear layer. Decreasing the amount of counterflow by increasing the spacing between the jets leads to a remarkable decline in the growth rates illustrating the effectiveness of the countercurrent in augmenting the mixing properties of shear layers. The enhancement in mixing rates of countercurrent shear layer was accompanied by the appearance of large turbulent structures in the shear layer and highly elevated fluctuating pressure levels, measured via fast response pressure probes. These results further illustrate the intimate connection between turbulent transport properties and shear layer growth rates.

4. The Structure of Heated Supersonic Jets Operating at Design and Off-design Conditions

The purpose of this investigation was to determine the effects of shock-cell structure and of temperature on the growth and development of a supersonic jet. The study used a two stage approach to introduce shock and expansion waves into the jet. First a single axisymmetric, convergent-divergent nozzle having a design exit Mach number of 2 is operated at three varying pressure ratios, corresponding to isentropic flow Mach numbers of 1.8, 2.0 and 2.15. In the second stage, three axisymmetric, convergent-divergent nozzles with matched throat areas and varying area ratios were utilized. These nozzles consist of the Mach number 2 nozzle as well as nozzles having design exit Mach numbers of 1.8 and 2.15. These nozzles operated at a constant pressure ratio corresponding to an isentropic Mach number of 2. Results indicate that shock cells in the near field do not significantly affect the growth rate the shear layers. Furthermore, flow in the fully developed region of the jet appear unaffected by the presence of shock cells. Increasing temperature ratio results in an increase of the jet spreading rates and centerline velocity decay. The Particle Image Velocimetry (PIV) data was found to be consistent with measured using probe instrumentation.

16

E. A Micromechanics Based Approach in the Representation of Deformation Processes in Advanced Materials

The investigators for this project have developed and used novel microscopy and texture/microtexture analyses together with advanced mechanical testing (load relaxation,...) techniques to investigate the relationship between processing, texture, microstructure and mechanical properties, in an effort to improve the mechanical properties of advanced aerospace materials. These materials include High Temperature Titanium Aluminide (and their composites) and aluminum based superplastic materials (Al-8090 and Al-7475). The optimization process is accomplished through the measurement of some characteristic of internal materials parameters at several stages of processing and related to their mechanical properties. The internal parameters important for parametrization may vary from one material to another. Two approaches have been used in the modeling effort, phenomenological and statistical mechanics approach. Our phenomenological approach uses real micromechanics interactions among mehanisms of deformation as a basis. Two microscopy techniques were developed and applied to measure phenomenological parameters from the microstructure and compared to mechanical testing results.

Introduction

The complexity of microstructure characteristic of polycrystalline materials presents the serious investigator with many challenges. The materials engineer hopes to associate the important technological properties of these materials with specific (quantifiable) attributes of the microstructure; however, microscopy presents an overwhelming myriad of details over a wide range of scales of inquiry. Other analytical techniques of characterization produce more information from the atomistic or molecular point of view. Thus the persistent question becomes: What is important in the microstructure relative to a specific property or aspect of material performance? One particular viewpoint, which stems from the modern atomistic interpretation of the structure of solids, is that for polycrystalline materials it is the spatial placement of lattice orientation that is of essential interest. Based on this micromechanics point of view the microstructure can be represented through a lattice orientation distribution function which can be used in a continuum approach to the structure property through proper averaging techniques.

We have concentrated on establishing novel experimental techniques to measure texture (macro, micro, and nano), residual stress (local and average), microplasticity, and (sub)grain boundary (high or low) morphology. These parameters have been measured by others for decades, but we believe that our techniques will allow us to measure them in local regions (a micron or less). These techniques include Backscattered Kikuchi Diffractometry (BKD), and Microscopic Strain Field Analysis (MSFA) using two important technological

17

development in Electron Microscopy and Imaging. Environmental Scanning Electron Microscope is a non-vacuum type electron microscope which can be operated at other mediums or temperatures. The imaging technology, Particle Imaging Velocimetry (PIV) was constructed by our Fluid Mechanics Group.

Of the two types of aerospace materials chosen for this study, superplastic materials required more attention to developing better mechanical testing techniques. Load relaxation has been identified as a better alternative compared to the strain rate change technique. The BKD technique and the new development in Orientation Imaging Microscopy provided information on Microtexture, (sub)grain morphology. It was possible to discover alternative deformation processes in Al-8090 to explain Superplastic forming. The results of texture were compared to that of x-ray to provide a better picture of the microstructural processes involved. A physically based phenomenological model was developed to represent superplasticity for all ranges of strain rates and temperature. The parameters of the model was related to the microstructure through grain size and a parameter related to the grain boundary characteristics. We believe that using a unique set of mechanical testing techniques (tensile, load relaxation and creep), all important materials parameters based on the proposed equation of state can be measured. We have compiled one of the most impressive mechanical testing facility to produce a large variation in strain rates (up to 8 decades) and temperature (4 degrees Kelvin to 1500 degrees C).

Titanium and Titanium Aluminides and their composites with superior properties (ultrahigh specific modulus, ultrahigh specific strength, high-temperature resistance, etc.) are essential materials in the advanced aerospace and automotive industries. In this project we have concentrated on a-2 and Gamma titanium aluminide because these materials are being considered as candidates for turbine applications. As in most processing, texture is introduced in these materials and may result in property anisotropy. A new processing technique (Plasma Cast Overflow) developed by NASA Langley is chosen to produce sheet materials. The difference in the coefficient of thermal expansion results in residual stresses and gradient in texture.

State Variable Approach

Testing methods to characterize the mechanical property of the inelastic flow of materials rely on the control of either displacement (rate), load (rate) , or some variation of these two parameters (true strain, stress, inelastic strain,...). These attempts are directed towards finding a relationship between the inelastic strain rate, $\dot{\varepsilon}$, and the applied stress, s, for different temperatures T. Following Hart [E1], the general form of such equations can be written in the following,

$$\dot{\varepsilon} = f(\sigma, d\varepsilon, T, X_i, \ ...) \tag{1}$$

Here de is the increment of the plastic strain, T is temperature and X_i's are parameters (internal state variables) which depend on deformation history and can be measured using proper testing methods. For a given temperature and at suitable conditions (where X's remain constant) a unique relationship can exist between stress and the inelastic strain rate which can be described by a plot of log s vs. log $\dot{\varepsilon}$.

We have developed a unified model based on Hart's past work [E2] which incorporates both superplasticity and matrix deformation. Such a model can predict both high temperature creep in addition to tensile deformation and room temperature plasticity. In this type of modeling all parameters can be obtained from a unique number of testing methods. It is our intention to include microstructural parameters like effective grain size and distribution as well as temperature. Specific to this model is the dependence to dislocation density through a hardness parameter called s*. As suggested by Hart the interrelation among the different parameters can be represented as a series-parallel model. We present a new version of the model in Figure 8, and this will be used in our work [E3].

If σ_{ij}^s and σ_{ij}^m are the sliding and matrix deviator stresses respectively, then, the specimen stress deviator σ_{ij} is given as:

$$\sigma_{ij} = y\sigma_{ij}^s + (1-y)\sigma_{ij}^m. \tag{2}$$

where y is a function of the volume fraction of the high angle grains with matrix deformation. We intend to determine the value of y phenomenologically using the experimental data. This involves a comparison of the grain size distribution for different misorientation angles.

The total strain rate is a combination of a matrix strain rate and the strain rate due to grain boundary sliding

$$\dot{\varepsilon}_{ij} = x\dot{\varepsilon}_{ij}^s + (1-x)\dot{\varepsilon}_{ij}^m. \tag{3}$$

where x is an anisotropy parameter.

Using the isotropic scaling law for each component of the rheological model, then

$$\dot{\varepsilon}_{ij}^k = \left(\frac{\dot{\varepsilon}_s}{\sigma_s}\right)\sigma_{ij}^k \tag{4}$$

where the superscript k corresponds to the sliding and the matrix deformation. The scalar relationships are:

$$\ln\sigma_m = \ln\sigma^* - \left(\frac{\dot{\varepsilon}^*}{\dot{\varepsilon}}\right)^\lambda$$

$$\dot{\varepsilon}^* = \left(\sigma^*/G\right)^m f\exp\left(-Q/RT\right) \tag{5}$$

19

$$\sigma_s = \sigma_s^0 \dot{\varepsilon}_s \qquad (6)$$

$$\sigma_s^0 = A \frac{kT}{\delta D_g} \left(\frac{d}{b} \right)^p , \qquad (7)$$

where d is the grain size, d_s the grain boundary width, D_g, the grain boundary diffusion, s^*, is the dislocation density hardness parameter, p, is the grain size exponent and is usually around 2-3, and $\dot{\varepsilon}_s$ and $\dot{\varepsilon}_m$ are assumed to have equal weights. The purpose of the modeling effort is to find the correct form of the σ_s^0, x and y. A graphical representation of the individual mechanisms of the proposed rheology and their composite behavior is illustrated in Figure 9.
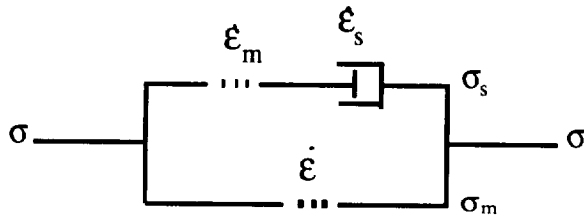
Modified Hart's Model (MHM)

Figure 8- The rheological model.
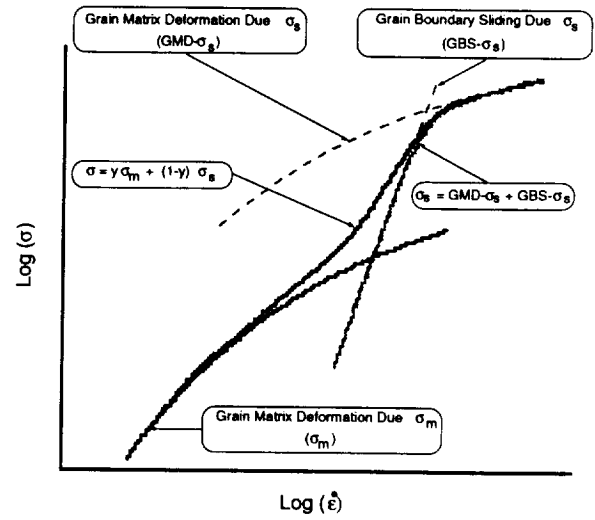
Figure 9- Composite mechanism.

20

Experimental Techniques

EBSP and OIM Techniques

The OIM technique is essentially an extension of the electron backscattered patterns (EBSP) technique[E4,E5]. Electron backscattered pattern (EBSP) in the SEM originates from elastically backscattered and diffracted electrons. These electrons are formed when stationary primary electron beam is made to hit the surface of a specimen inclined at 70°. The diffraction patterns are imaged on a phosphor screen placed close to it.

From this data, a map, called an OIM micrograph, is constructed displaying changes in crystal orientation over the specimen surface. In the OIM micrograph, the orientation of each point in the microstructure is known and hence the location, length and misorientation of all boundaries. This fully automated technique provides for the examination of the microtexture and mesotexture of large regions of the specimen (Figure 10).

(a)   (b)
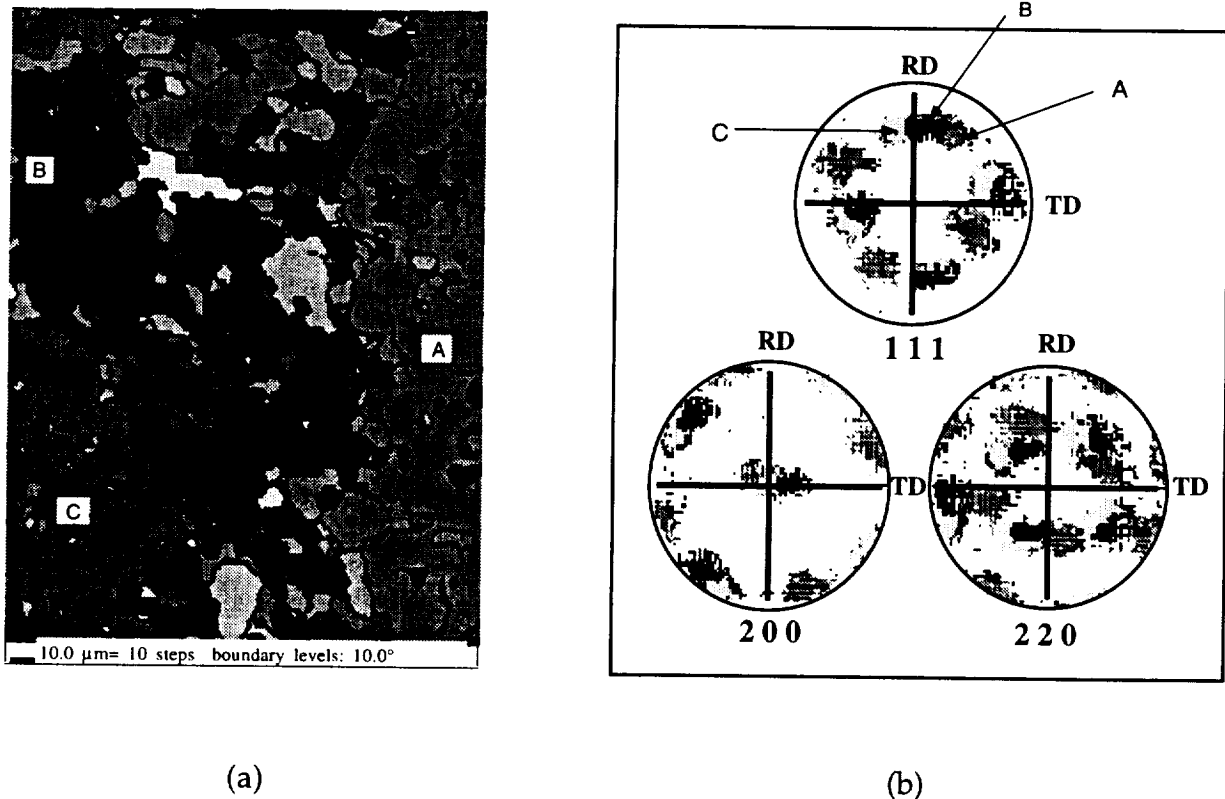
Figure 10- (a) 10 ° Misorientation boundary micrographs. (b) Pole figure representation of the previous figures. Dark gray, black and light gray represent the three right, top right and bottom left coarse regions.

The experiments performed above can be analyzed to provide information on the nature of the grain boundaries and distinguish the high angle grain boundaries which are candidates for grain boundary sliding. we have been

21

able to measure the grain size and the parameter y in the model above from these data.

Microscopic Strain Field Analysis

We have developed a technique for microscopic strain field analysis (MSFA) which combines in situ heating or straining in an Environmental Scanning Electron Microscope (ESEM) with digital image processing [E6]. This technique can be used to investigate the granular and intergranular strain localization during deformation. Figure 11 is a schematic which illustrates the application of MSFA to measure thermal strains in inhomogeneous materials. An ElectroScan model E-3 Environmental Scanning Electron Microscope (ESEM) equipped with a heating and/or tensile stage, is used to image the specimen in a strain-free state and in a strained state. A digital micrograph of the region of interest is collected for each state. These images can be collected in real time (10 pictures per second) using a SGI computer interface.

The cross correlation function [E7] is calculated for interrogation regions over the entire image to produce a map of the local displacement. Displacements are displayed as an array of vectors. The displacement gradients and the subsequent components of strain are calculated using a finite difference approach.

Strain-free   Strained

1. ESEM in situ straining experiments, collection of digital images of strained and strain-free microstructures.

2. Cross correlation of digital micrographs to obtain local displacements.

3. Differentiation of displacements to obtain isostrain contours.
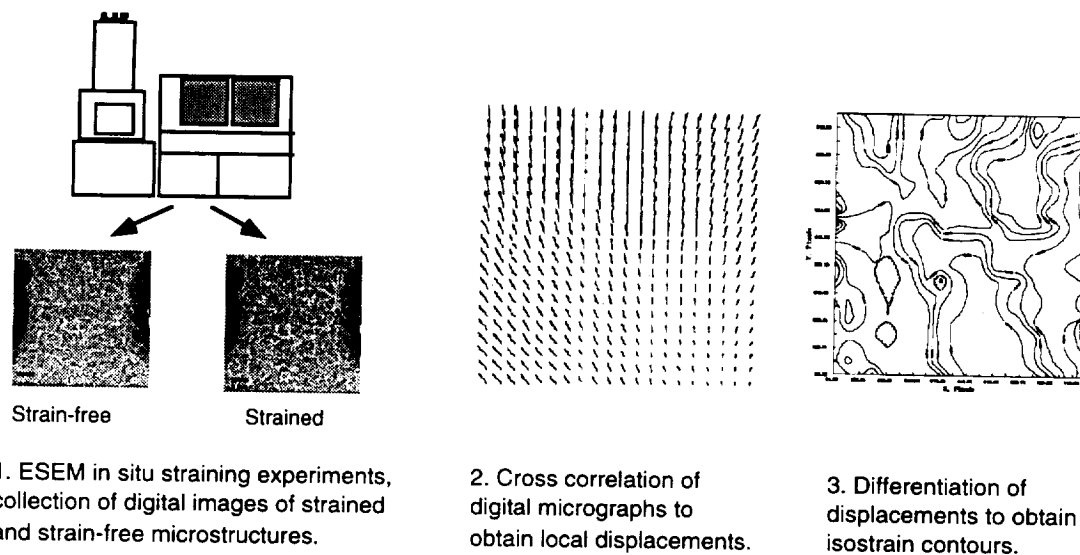
Figure 11- Schematic of MSFA for measurement of thermal strains in inhomogeneous materials.

References:

[E1]   E. W. Hart, *Acta Metallurgica* , September, vol. 15, pp. 1545-1549, 1967.

[E2]   B. P. Kashayap, A. Arieli, A. K. Mukherjee, Journal of Materials Science, vol. 20, pp. 2661-2686., 1985.

[E3] H. Garmestani, P. Kalu, F. Booeshaghi, Materials Science Forum, vol. 243-245, pp. 569-574.

[E4] J. A. Venebles and C. J. Harland, in *Phil. Mag.*, vol. 27, 1973, pp. 1193-1200.

[E5] H. Garmestani, P. N. Kalu, and D. Dingley, presented at Proceeding of the Light Weight Alloys for Aerospace Applications III, 124th Annual Meeting of TMS, 1995, Feb 12-16.

[E6] K. Harris, H. Garmestani, and L. Lourenco, "Microscopic Strain Field Analysis for In Situ ESEM Investigation," *to be submitted to the Journal of Experimental Mechanics*.

[E7] L. Lourenco and A. Krothapalli, "On the accuracy of velocity and vorticity measurements with PIV," *Experiments in Fluids*, vol. 18, pp. 421-428, 1995.

F. Nonlinear and Nonequilibrium Phenomena in Supersonic Flow

The research at LMFP is focused on high speed gas dynamics and collisional plasmas with special emphasis on the development of new diagnostic techniques and the fundamental fluid physics of turbulent transport, turbulent quantum effects, and supersonic flow. New diagnostic techniques have been confirmed including 3D Phase Coherent Velocimetry and 3D Direct Estimation Velocimetry for high speed shear flow. In the following sections, we give an overview of these activities, including motivation and recent results [F1].

1. Turbulence and Condensation

Heterogeneous nucleation and the subsequent droplet and crystal growth play a critical role in the contribution from PCS and vapor trails to atmospheric environmental concerns and in the development of ice crystals on environmentally exposed aerofoils. Yet, the best growth rate theories are essentially ad hoc and/or empirical with very weak experimental confirmation of underlying physical principles. We have begun to test and extend these theories.
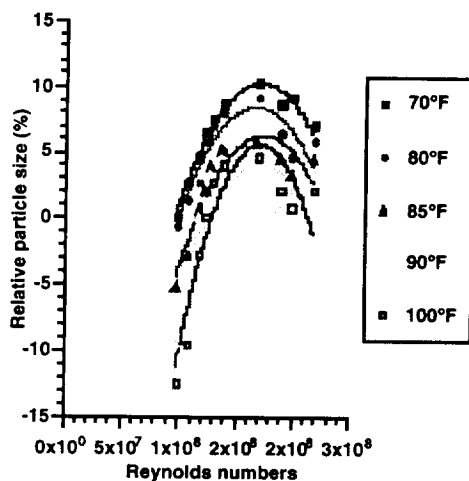
Figure 12. Turbulence influence on the condensate particle size.

For this, we take advantage of our considerable existing capabilities and facilities for shock tube flow analyses and control. Specifically, we are using our 5" pressure ruptured shock tube so that measurements can be made on the growth of droplets in real time in the shock tube's expansion fan. For this, we modify our driver section test chamber so as to afford humidity and temperature control. We are making Mie scattering measurements, using our 18 Watt all lines Argon Ion laser and appropriate analytical and calibration procedures, so as to provide continuous recordings of droplet size and density at the measuring stations. Off-line reconstructions are performed, using appropriate computer software and hardware, so as to provide histories in the droplet frame of reference using the velocity calculated from the assumptions of one-dimensional shock tube flow and confirmed by direct LDV. From these results, we obtain droplet growth rate data and a droplet growth rate model which will determine the roles of temperature and suspensions in the evolution of droplets.

We have found a new clear dependence of droplet size on the strength of the turbulence. As Fig, 12 above shows, increasing Reynolds number produces an increase in the relative sizes of the droplets in a manner which changes with temperature and changes with Reynolds number according to a standard strong coherence model. Furthermore, when the rate of droplet growth is measured by

observing the change in droplet size at two locations, we find that the rate of change of droplet size is also dependent on the Reynolds number. (See Fig. 13.) We show a temperature sensitivity in these results also. We expect, with this motivation and these results, to extend our investigations to low temperature regimes; we are particularly interested in the pressure and temperature conditions appropriate to sublimation. Under these conditions we expect to determine the role of both turbulence and temperature in the evolution of ice crystals, appropriate to high altitude jet trails and to the onset of icing on the wings of airplanes.
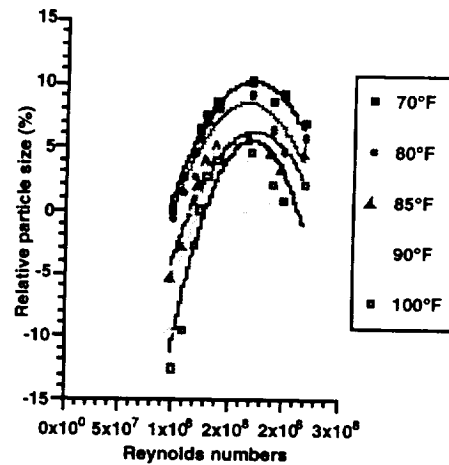

Figure 13 Turbulence influence on the rate of change of droplets

2. Compressible Turbulent Flow

Advances in turbulence physics are now intimately connected to the availability of comparisons between theoretical models and realistic generalizable experimental data. In particular, a rank ordering of modeling approximation techniques for strong turbulence requires a dedicated relationship between theoretical approaches and experimental facilities where the approaches can be tested. We have arranged to provide such a testing ground. We have confirmed the applicability of our diagnostic procedures, (phase coherence velocimetry, or PHACO, and direct estimation velocimetry, or DEV) to turbulent compressible flow using our existing Ludwieg tube facility while implicitly showing the feasibility of these techniques for large scale facilities of the sort which are in use at NASA Research Centers.

Using DEV, we have performed simultaneous measurements of density and all components of velocity from laser induced fluorescence at a data rate in excess of 2 MHz in a turbulent supersonic free shear layer. A sample of these data is given in Fig. 14. We thereby measure, with profound spatial and temporal resolution, the turbulent transport in a manner which will be useful for a wide variety of flow fields. Bursting effects are suppressed and the triple correlations remain near zero throughout the flow. Thus, our newest data show clear evidence of a vanishing triple correlations. The averages of triple correlation terms $<\rho'u'v'>$ and $<\rho'u'w'>$ in consecutive time intervals are shown in Fig. 15; specifically the average value is 0.029 ± 0.04 which is statistically consistent with the prediction of a vanishing tri-

Figure 14. Evidence of the vanishing triple correlation.

-25-
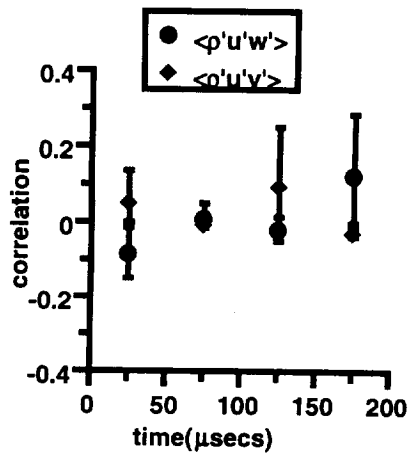
Figure 15. Evidence of the vanishing triple correlation.

ple correlation. Thus, these measurements offer a first tentative confirmation of the validity of predictions on the closure issue in compressible turbulence in the theoretical approach first offered by Tsugé and Sagara. These results should therefore prove quite useful in the current efforts at enhancing the broad applicability of physics models for compressible turbulent flow.

From these data, we can also provide time histories of one component of vorticity at fixed locations in the free shear layer. We are able to immediately extend these procedures so as to provide high data rate two dimensional spatial maps of Reynolds stresses and one component of velocity using a CW laser-induced fluorescent sheet. We can in fact provide all these data, as required, at Mach numbers of interest throughout the critical range 1.5<M<2.5. We are also able to extend our techniques to the measurement of three instantaneous components of vorticity. Such data would stand on its own merit but would also be particularly appropriate in comparisons with some of the CFD predictions.

3. High Density Plasma Processes

A new research effort has begun using the FAMU arc-driven shock tube in collaboration with theoreticians and experimentalists at the University of Chicago and Princeton Plasma Physics Laboratory on new diagnostics and new turbulence models for high density ionized gases. There are deep short-falls in the completeness of current theoretical models for high density plasma processes especially with regard to nonlinear and nonequilibrium phenomena and the physics of electron and atomic

Figure 16. Phase Space trajectory of a chaotic plasma process.

scattering by ions. There are also profound limitations in current analytical and diagnostic procedures for the high density ionic systems. We have therefore initiated a comprehensive and synergistic series of investigations on the creation, diagnostics, collision dynamics, and control of prospective high density plasmas, both as flow systems and also as targets for impinging beams of neutral, charged, and excited particles.
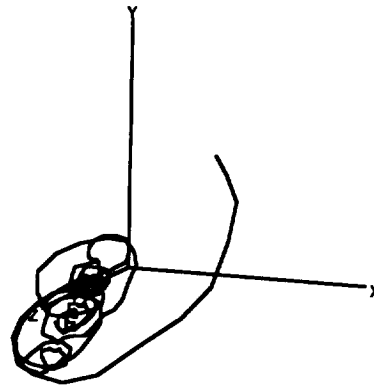
We have already seen an unexpected persistence in the robustness of chaotic dimension as a characterizing parameter in steady state turbulence. In Fig. 16, one sees a typical 3D phase space projection of a seven dimensional reconstruction of

one dimensional density evolution in a turbulent collisional plasma. Over a variety of operating conditions, as suggested in Fig. 17, the chaotic dimension is essentially constant, confirming our previous observations on the reliability of this parameter as an index for a turbulent state.

4. Interaction of Turbulent Plasma Flow with a Hypersonic Shock Wave

Considerable interest exists in the interactions of shock waves with turbulent gases and plasmas[F2] and with turbulent interfaces [F3]. Various theoretical approximations have been used to explore specifically the interactions of shock waves with continuous incompressible turbulent flow systems [F4, F5, F6]. For stationary collisional plasmas, the conventional Reynolds number is irrelevant under circumstances where the standard features of turbulence in ordinary gases are observed in the plasma [F7]. In addition, for compressible turbulence, the recent evidence of vanishing triple correlations [F8] suggests that the role of compressive effects ordinarily associated with the shock wave could be significantly muted by the existence of a strongly turbulent local environment. We have therefore explored the influence of a reflected shock wave on the turbulence produced behind an ionizing shock wave of the sort previously reported [F9].
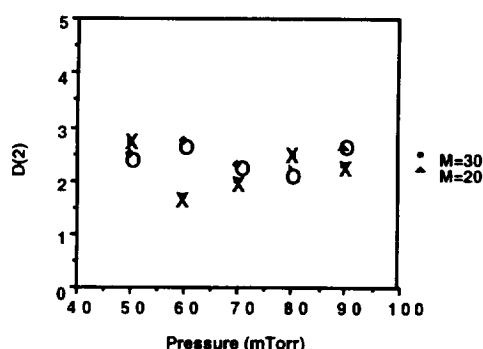
Figure 17. Chaotic persistence in steady turbulence.

In our experiments, a hypersonic shock wave is produced by discharging a 14.5 µF capacitor that has been charged to 18 KV into an argon gas filled cylindrical tube 5 cm in diameter and about 200 cm long. In this arc driven shock tube, the speed of the shock wave depends on the pressure of the gas inside the tube and the charging voltage. As the shock wave propagates down the tube it compresses and heats the gas. We choose operating conditions such that $M_S=19.62$ (M_S is the Mach number of the primary shock wave), based on direct measurements of the primary shock wave's speed (W_S) and the room temperature. We also make a direct measurement of the speed of the reflected shock wave (W_R). Using standard calculational procedures for this kind of flow environment [F10], we confirm that the approximate specific heat ratio $\gamma = 1.333$ is obtained as appropriate for a fully ionized plasma.

We used laser induced fluorescence (LIF) as our principal diagnostic technique representing local density fluctuations. The fluorescence signal is collected at a 50 MHz sampling rate from a window that is perpendicular to the incoming laser and then focused at the entrance of an adjustable monochro-

-27-

mator set at 422.8 nm; the subsequent filtered optical signal is picked up by a photomultiplier tube providing input to the digitizing oscilloscope with a 50K per channel data point storage capacity. The slope of the power spectrum for the turbulent density fluctuations was computed by fitting the power spectrum to $P \propto \omega^{-n}$ where n is the power spectral index. The fractal dimensions were calculated using the standard Grassberger-Procaccia correlation function to estimate the degree of complexity of our data [F11].

The detailed mechanisms providing the source of turbulence are not yet known; however, reaction-diffusion processes arising from the nonequilibrium recombination $Ar^- + e^- + X \rightarrow Ar + X$ (the onset of which increases the dimensionality of the system) have a relaxation time scale appropriate (when compared with the local flow time) for increased chaotic complexity in the system and correspondingly for the development of turbulence.

In Figs. 18 and 19 are presented the evolution of density power law index n and the chaotic correlation dimension for all the experiments; the errors indicated include systematic effects arising from shock-to-shock variations in the measured parameters with identical starting conditions. In both cases, the first point in the graph corresponds to data taken when the primary shock wave reached the optical window; each turbulence parameter determination was calculated on 256 data points separated by 25 μs. In both cases, it is easy to distinguish the regions before and after the reflected shock wave; there is no relaminarization. It is also easy to see that the reflected shock wave causes a transient increase in the two turbulence parameters followed by a period of relaxation toward pre-reflected shock wave values. The higher value of spectral index suggests that interaction of the shock wave with the plasma tends to increase the rate of transfer of energy through the turbulent scales. The higher value of the fractal dimension suggests that the interaction of the shock wave with the plasma tends to increase the degree of complexity of its turbulence. Although there is no theoretical explanation available at present for the slopes of the curves in Figs. 18 and 19, generally stated, these numbers all fall within the expected values for turbulent flows.

However, a distinction can be made in the behaviors shown. Specifically, the rate of change before and after the reflected shock wave is the same for the parameter n; the rate of change before and after the reflected shock wave is quite different for the parameter D_2. As previously noted, the temperatures, number densities, and velocities before and after the reflected shock wave are quite different. Therefore one might infer that the chaotic dimension as a turbulence indicator is sensitive to the full range of ordinary macroscopic parameters. By contrast, one might infer that the spectral index n is a fundamental indicator of the turbulent energy transfer processes, dependent only on the microscopic (molecular) constituents.

-28-
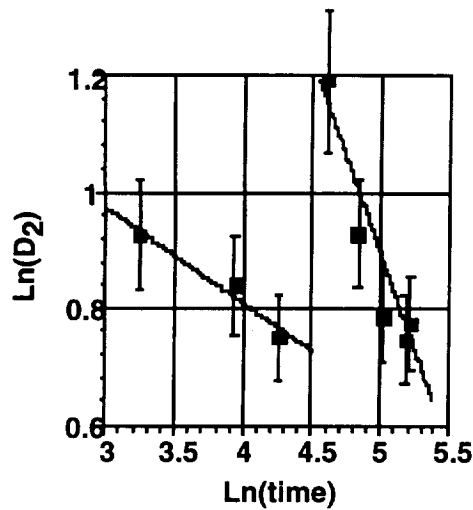
Figure 18. D_2 Changes for Reflected Shock
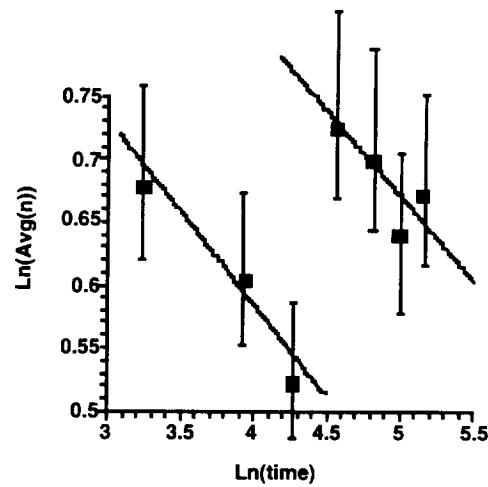
Figure 19. n Changes for Reflected Shock

References

[F1] See the CeNNAs Bibliography, Appendix A, for detailed citations.

[F2] S. Barre, D. Alem and J. P.Bonnet, AIAA Journal, **34**, 968, (1996) and references cited therein.

[F3] M. Vetter and B. Sturtevant, Shock Waves, **4**, 247 (1995).

[F4] S. Lee, S. K. Lele and P. Moin, AIAA Paper 94:0311 (1994)

[F5] S. K. Lele, Phys. Fluids A, **6**, 1052 (1994)

[F6] J. A. Johnson III, L. E. Johnson and Z. Liang, Shock Waves, Proceedings, Sendai Japan, 1991/Vol. II, (K. Takayama, ed.), pp 1307-1312 (Berlin; Springer-Verlag, 1992).

[F7] J. A. Johnson III and R. Ramaiah, Phys. Rev. A, **36**, 774 (1987).

[F8] U. De Silva, J. Zhang, J. C. Orou and J. A. Johnson III, J. Phys. D: App. Phys., **29**, 263 (1996)

[F9] J. A. Johnson III, Lin I and J. P. Santiago, J. Phys. D: Appl. Physics, **23**, 662 1990

[F10] H. J. Pain, The Physics of Vibrations and Waves, pp 372-374 (John Wiley and Sons, 1983)

[F11] J. A. Johnson III, L. E. Johnson and Y. Hong, Phys. Letts., **158**, 144 (1991)

IV.
Scientific Workforce Development

One of the center's objectives was to increase the numbers of underrepresented minorities acquiring Ph. D.s in both Physics and Engineering. Toward this end programs were established for each level of academic preparation: Undergraduate, Masters and Ph. D. During the five year funding period for CeNNAs, fifty-four students participated with thirty-nine graduating from at least one level of training. For a complete student-by-student listing, see Appendix B; in this section we focus on some of the statistical details in our student productivity.

The Center offered three programs: 1) undergraduate research internships; 2) graduate research assistantships; 3) summer research internships. Overall, the CeNNAs students fall into one of two groups: 1) those who are currently studying with a CeNNAs faculty member; 2) those who have completed their study at Florida A & M and are continuing at a second institution. The latter group is comprised for the most part of most students who completed their undergraduate training at FAMU and the graduates from the M.S. program in Physics at FAMU. It also includes students who did not matriculate at FAMU but who had significant academic year and/or summer research experiences at FAMU with CeNNAs support.

1. Students at CeNNAs

Undergraduate Experiences-

The undergraduate interns came from the pool of academically superior students who are recruited to study at Florida A & M University. Each maintained a minimum 3.2 grade point average and contributed ten hours per week to on-going research as a member of a CeNNAs research team. By the end of the third semester, each undergraduate delivered at least one scientific talk at the center and many gave talks at scientific conferences. The center faculty continue to have a commitment to this group while they pursue further training.

During the five years, thirty-four undergraduates participated. Twenty-four (.71) graduated with the remaining ten (.29) still enrolled. Of the graduates, sixteen (.67) enrolled in graduate school with fourteen of the sixteen (.88) working on either a Physics or an Engineering degree, one pursuing medicine and one studying patent law. See Table I. Undergraduate CeNNAs graduates attend: Brown, Emory, Florida A & M, Georgia Institute of Technology, Harvard, Massachusetts Institute of Technology, Stanford, University of Minnesota and Virginia Polytechnic Institute.

30

Undergraduate Interns			
	Participants	Of Graduates	Grad.s In Grad. School
Male	25 (.74)	19 (.79)	12 (.75)
Female	9 (.26)	5 (.21)	4 (.25)
TOTAL	34	24	16

Table I

All of the students were members of underrepresented minorities. Thirty-one of the students (.91) were citizens. The remaining three, two female and one male were permanent residents. See Table II.

Undergraduate Ethnic/Sexual Representation
---------------- Underrepresented Minorities ----------------

Sex	Afr. Amer.	Hispanic	Pacific Is.	Perm. Res.
Male	22	1	1	1
Female	7			2
TOTAL	29	1	1	3

Table II

Many of the students that completed their Florida A & M training and went to graduate school keep in contact with CeNNAs. Their tenure in CeNNAs assured them that the faculty was serious about nurturing them through their Ph.D.s. Moreover, through many discussions, the students learned both to distinguish quality graduate training and to gather information so as to make wise choices in their professional training. Encouraged to actively chart the most successful courses, many have given evidence that they listened quite attentively. Faculty members get calls and e-mail regularly from many who want to discuss thoughtful issues related to their scholarly pursuits. One student, for example, identified a prospective Ph.D. advisor at her graduate institution. When she learned the professor would be in Tallahassee for a weekend, she arranged for her CeNNAs mentor to talk with him. She wanted assurances that her instincts were correct.

Other former students voluntarily recruit students for the CeNNAs program. For example, at the 1997 National Society of Black Student Physicists Meeting, several graduates worked in the FAMU graduate recruitment booth. Some seek advice on crucial professional decisions, others advise their less experienced colleagues on selecting graduate programs, while some simply make a point of enjoying the emotional support of current participants.

31

Graduate Student Experiences-

The graduate program provides traditional research opportunities for students pursuing the Masters degree in Physics and the Masters and Ph. D. degrees in Mechanical Engineering by providing both mentoring and funding for research. Each student is required to present talks at professional meetings. Each student is strongly encouraged to published in refereed journals prior to graduation. For Ph.D. students, publications are mandatory.

The Masters programs have trained altogether fifteen students during the funding period. Seven of these have graduated, five are still currently matriculating and three discontinued their studies prior to completion. See Table III.

Performance of Masters Students

	Received Masts.	Currently Studying	Unfinished and Left
Physics	2	2	1
M. E.	5	2	1
Other		1	1
Male	6	4	3
Female	1	1	-
Citizen	6	3	3
Permanent Res.	1	1	-
Foreign	-	1	-

Table III

During the funding period, nine Ph. D. students studied with CeNNAs faculty. Four finished their studies and earned their doctorates, two in Physics and two in Mechanical Engineering. Of this group of new CeNNAs driven scientists and engineers, all were males, two were citizens, one was a permanent resident and one was a foreign national. There are four students still in the program. Of these, three have passed their qualifying exams and all four have dissertation topics. See Table IV.

Performance of Ph. D. Students

	Received Ph. D.s.	Currently Study-ing	Unfinished and Left d
Physics	2	1	
M. E.	3	3	1
Male	5	4	-
Female	-	-	1
Citizen	2	3	1
Permanent Res.	1	-	-
Foreign	2	1	-

Table IV

Summer Activities-

In the summer intern program, undergraduates participated in research. The program had two principle objectives. First, the students who participated in our programs during the academic year, needed to have extended period during which to practice science. The summer provided this period for them. Second the program was used as a recruitment vehicle to encourage students from other schools to learn, first hand, about the unique opportunities which graduate study at Florida A & M provides. Each student participated full-time on a research team with efforts which culminated in a scientific talk at the end of the summer. It was during these summer activities that prospective scientists had a chance to acquire disciplined research habits, to resolve challenging intellectual problems, to experience the frustrations which go along with demanding research tasks and to also experience the joy and exhilaration derived from solving complex problems with the possibility of contributing to new knowledge .

In addition, based on their own testimony and confirmed by observations of CeNNAs faculty, students were able to stretch their intellectual and research capabilities so as to provide evidence to themselves that they could study science and engineering. With the successful completion of each new demanding effort, the young scientists gained insight into their capabilities. With each successful completion, the students had further assurances that challenging problems can be resolved through hard work , intensive study and deep reflection. Through these experiences young students were encouraged and came to see themselves as having control through disciplined effort. Most importantly, the students experienced the joy and exhilaration that comes from succeeding and gaining insight from demanding study.

2. Students Continuing Study at A Second Institution of Higher Learning

Twelve students left FAMU CeNNAs and have studied at other universities. Nine completed or are completing work on the Masters Degree. Four females received Masters and five males are still completing their work. One was in Physics, four in Mechanical Engineering and four were in other fields. All but one of these are U.S. citizens. See Table V.

The students attend or have attended: Emory University; Georgia Institute of Technology; Harvard University; Universities of Colorado, Maryland, and Minnesota; Vanderbilt University; and Virginia Polytechnic Institute. There are four CeNNAs students working on Ph. D.s at other institutions, three in Physics and one in Electrical Engineering. Two have completed their qualifying exams and one of these has a dissertation topic. Three are citizens, one male and two females. One male is a permanent resident. The students attend Brown and Stanford Universities, Georgia Institute of Technology, and The Massachusetts Institute of Technology.

Performance of Masters Students at Other Institutes of Higher Learning

	Received Masters.	Studying	Unfinished and Left
Physics	1	-	-
M. E.	2	2	-
Other	1	3	-
Male	-	5	-
Female	4	-	-
Citizen	3	5	-
Permanent Resident	1	-	-
Foreign	-	-	-

Table V

V.
Leveraged Funding

The NASA-FAMU Center for Nonlinear and Nonequilibrium Aeroscience has structured its research program to maximize its impact, short and long-term, on industry, particularly industrial practice and products. In this, we have developed relationships so that the people, techniques and ideas generated in the CeNNAs setting will bring maximum value to other settings: industrial first, but also governmental and educational. To do this, our job has been:

1. to develop new means of understanding and manipulating aeronautical systems which might be of broad economic usefulness in the intermediate or long run, complementing the short term focus of aeronautical science;

2. to communicate effectively with those who use aeronautical science commercially, that they may both exploit our findings and guide us in choosing research directions;

3. to train our students to meet the needs of a variety of prospective employers, notably small technology-using businesses; these trained students are a major avenue for the transfer of our new knowledge;

4. to grasp short-term opportunities insofar as they are helpful to longer term goals; however, generally speaking, we do not expect that this 'short-term' outreach will be a major portion of our activity.

The overall approach just affirmed is a new public consensus, well established as the partnership plan for a variety of new generation federally funded science and technology centers and is not original with CeNNAs. Nonetheless, in the spirit of 'not re-inventing the wheel,' we have adopted this approach completely as our own. We have been particularly alert to opportunities for partnership which are directly derived from our interactions with NASA scientists and engineers.

Our successes in this effort are reflected in part by the leveraged funding which we have achieved. See Appendix C. The program of partnerships will clearly enhance the research programs through the infusion of ideas ordinarily associated with collaborations and through the continuously refreshing impact on the subjects and focus of our investigations. Through carefully chosen packaging and the inclination to explore variations on the themes which are being established by the Center, the partnerships are providing a variety of options for leveraging Center funds and new opportunities for our faculty and students which are quite substantial indeed.

Appendix A

CeNNAs Bibliography

CeNNAs Bibliography

Alvi, F. S., Krothapalli, A. and Washington, D., "An Experimental Study of a Compressible Countercurrent Turbulent Shear Layer", AIAA Paper 95-0580, AIAA Journal 34 (4) pp.738-745, 1996.

Ammons, E., "Wilson Renormalization Group Approach to Light-front Tamm-Damcoff Scalar Field Theory", Phys. Rev. D 50 pp.980, 1994.

Ammons, E., "Bloch-Wilson Renormalization of Tamm-Dancoff Light-front QED", Phys. Rev. D, 54 pp.5153, 1996.

Ammons, E., "Model of the Measurement Process in Quautum Mechanics", Submitted to Physica Scripta.

Ananth, C.R. and Chandra, N., "Evaluation of Interfacial Shear Properties of Metal-Matrix Composites from Fiber Push-out Tests", Mechanics of Composite Materials and Structures 2 pp.309-328, June 1995.

Ananth, C.R. and Chandra, N., "Numerical Modeling of Fiber Push-Out Test in Metallic and Intermetallic Matrix Composites--Mechanics of the Failure Process", Journal of Composite Materials 29(11) pp.1488-1514, 1995.

Ananth, C.R. and Chandra, N., "Elevated Temperature Interfacial Behavior of MMC: A Computational Study", Composites - Part A 27A pp.805-811, 1996.

Ananth, C.R., Chandra, N. and Garmestani, H., "Process Induced Residual Stresses in Metallic/Intermetallic Matrix Composites", Computational Plasticity: Fundamentals and Applications, Editors: D.R.J. Owen et. al., Pineridge Press, 1992, pp 2205-2216.

Ananth, C.R., Chandra, N., Murali, K. and Garmestani, H., "Effect of Inelastic Material Behavior on Residual Stresses in Metal Matrix Composites", Advanced Composites '93: Proceedings of the International Conference on Advanced Composites, Editors: T. Chandra and A.K. Dhingra, The Minerals, Metals and Materials Society, 1993, pp 1317-1324.

Ananth, C.R., Mukherjee, S. and Chandra, N., "Effect of Time Dependent Matrix Behavior on the Evolution of Processing-Induced Residual Stresses in Metal Matrix Composities", Journal of Composites Technology and Research , 1996.

Baluja, K. L., Jain, A., Jones, H. W., Weatherford, C. A., and Amaya-Tapia, A., "Electron Scattering from Krypton Atoms Between 1-20 eV", Physica Scripta 45 pp.30-34, 1992.

Belay, K., Williams, R. and Johnson, III, J. A., "Interaction of Turbulent Plasma Flow with a Hypersonic Shock Wave", J. of Appl. Phys. 81 pp.1073-1076, 1997.

Bouferguene, A. and Jones, H. W., "On Lowdin Alpha Functions: Series Representations and Convergence Analysis", Submitted to J. Math. Physics.

Cao, G., O'Reilly, J.W., Crow, J.E., Kennedy, R.J., and Nichols, D.H., "Unusual Transport and Magnetic Properties of Tb-doped YBa2Cu3O7-x Single Crystals and Epitaxial Thin Films", J. Appl. Phy. 75 pp.6328, 1994.

Castellanos, A., Johnson, L.E. and Johnson III, J.A., "Coupled Ion Density and Neutral Light Emission Fluctuations in a Collisional Turbulent Plasma", Rev. Sci. Instru (To Be Published).

Castellanos, A., Johnson, III, J. A. and Johnson, L. E., "Evolution of Turbulent States in a Glow Discharge Tube Plasma", Submitted to Applied Physics Letters.

Chandra, N. and Ananth, C.R., "Analysis of Interfacial Behavior in MMCs and IMCs Using Thin-slice Push-out Tests", Composites Science and Technology 54 pp.87-100, 1995.

Chandra, N., Ananth, C.R. and Garmestani, H., "Micromechanical Modeling of Process-Induced Residual Stresses in Ti-24Al-11Nb/SCS-6 Composite", Journal of Composites Technology and Research 16 pp.37-46, January, 1994.

Chandra, N. and Dang, P., "Application of Micromechanical Model to High Strain Rate Superplastic Materials", Scripta Materialia , 1996.

Chandra, N. and Kannan, D., "Superplastic Sheet Metal Forming of Generalized Cup, Part II: Non-Uniform Thinning", Journal of Material Engineering and Performance 1 pp.813-822, 1992.

Chandra, N. and Kannan, D., "Superplastic Sheet Metal Forming of Generalized Cup, Part I: Uniform Thinning", Journal of Material Engineering and Performance 1 pp.801-812, 1992.

Chandra, N. and Murali, K., "A Micromechanistic Model of Superplastic Behavior in Pseudo Single Phase Aluminum Alloys", Scripta Metallurgica et Materialia 9 pp.1429-1434, 1995.

Chandra, N., Murali, K. and Garmestani, H., "Experimental and Numerical Investigation of Superplastic Deformation Mechanisms", Materials Science Forum 170-172 pp.47-52, 1994.

Chandra, N. and Rama, S.C., "Application of Finite Element Method to the Design of Superplastic Forming Process", ASME Journal for Engineering and Industry 114 pp.452-459, 1992.

Chandra, N., Rama, J. and Dang, P., "Application of Micromechanical Polycrystalline Model in the Study of Threshold Stress Effects on Superplasticity", Material Sci. Eng. A , 1996.

Chandra, N. and Xie, Z.Y., "Application of Superposition Method to the Thermal Residual Stress Problem in Composites", Advanced Composites '93: Proceedings of the International Conference on Advanced Composites, Editors: T. Chandra and A.K. Dhingra, Warrendale, PA, 1993, pp 323-327.

Chandra, N. and Xie, Z., "Development of Generalized Plane Strain Tensors for the Concentric Cylinder Inclusion Problem", ASME Journal of Applied Mechanics.

Chella, R., Aithal, R. and Chandra, N., "Evaluation of Fracture Parameters of Composites Subjected to Thermal Shock Using Boundary Element Method and Sensitivity Analysis Techniques", Engineering Fracture Mechanics 44 pp.949-961, 1993.

Clayton, C.E., Marsh, K.A., Dyson, A., Everett, M., Lal, A., Leemans, W.P., Williams, R. and Joshi, C., "Ultrahigh-Gradient Acceleration of Injected Electrons by Laser-Excited Relativistic Electron Plasma Waves", Phys. Rev. .

Cox, A., Garmestani, H., Markiewics, D. and Dixon, I., "Multi-Axial Investigation of High Field Composite Solenoids", Proceedings of the Second International Conference on Composite Engineering.

De Silva, U., Gardner, A. and Johnson III, J.A., "Turbulent Manupulation of Condensation at a Shock Tube's Contact Surface", AIAA Journal 33 pp.368-370, 1995.

De Silva, U., Zhang, J., Orou, J.C. and Johnson III, J.A., "Evidence of Natural Closure in compressible Turbulent Flow", Submitted to Journal of Physics D.

Etemadi, B. and Jones, H.W., "Accurate LCAO Ground State Calculations of HeH2+ Using Slater-type Orbitals", Int. J. Quantum Chem.Symp. 27 pp.755, 1993.

Garmestani, H., "A Unified Model for Cyclic Loading and Relaxation - A State Variable Approach", Submitted to Journal of Engineering Materials and Technology.

Garmestani, F., Booeshaghi, F. and Kalu, P., "Micromechanical Investigation and Phenomenological Modeling of A1-8090 Superplastic Materials", Materials Science Forum 243-245 pp.569-574

Garmestani, H., Harris, K. and Kalu, P., "Orientation Imaging Microscopy in Environmental Scanning Electron Microscopy", Journal Scanning Microscopies 20(1), 1996.

Garmestani, H., Kalu, P. and Dingley, D., "Micro-characterization of A1-8090 Superplastic Materials using Orientation Imaging Microscopy", Accepted for Publication in the Journal of Materials Science and Engineering.

Garmestani, H. and Kuhlhoff, J., "Mechanical Testing of Superplastic Materials over Large Strain-Rate Ranges", Submitted to International Journal of Engineering Materials and Technology.

Garmestani, H., Lin, S. and Adams, B., "Statistical Continuum Theory For Inelastic Behavior of A Two-Phase Medium", Accepted for Publication in the International Journal of Plasticity 1 pp.183, July , 1994.

CeNNAs Bibliography

Garmestani, H., Sohi, G.S., Mukherjee, S. and Chandra, N., "Investigation of Deformation Mechanisms of Superplastic Materials Using Diffraction Patterns' ", Superplasticity and Superplastic Forming of Advanced Materials, Editors: N. Chandra et. al, TMS Publishers, 1993, pp 109-120.

Garmestani, H., Vaghar, R. and Markiewics, W.D., "Concepts of Plasticity in Solenoid Stress Analysis", IEEE Transactions on Magnetics 30 pp.2237-2240, July 1994.

Garmestani, H., Vaghar, R., Markiewics, D. and Chandra, N., "Stress Analysis of an Anisotropic Work Hardening Cylinder with Body Forces", International Journal of Mechanics of Structures and Machines. 23(4), 1995.

Halliwell, M., Kennedy, R.J. and Bassignana, I., "Xray Characterization of Imperfect Heteroepitaxial Layers", Submitted to Proceedings of the 44th Annual Denver X-Ray Conference, Colorado Springs.

Hart, E.W. and Garmestani, H., "Mechanical Testing Using Direct Control of the Inelastic Strain Rate", Journal of Experimental Mechanics pp.1-6, March 1993.

Hazoumé , R. and Johnson III, J.A., "Condensate Droplet Growth with Temperature Fluctations", Submitted to Physics Letters.

Hazoumé, R. and Johnson III, J.A., "Turbulence and Condensation at a Tangential Discontinuity", Submitted to Journal of Applied Physics.

Huo, W.M. and Weatherford, C.A., "Variation of the projection parameter in a Schwinger multichannel method", Submitted to Physical Review A.

Johnson, J.A., Belay, K. and Williams, R.L., "Turbulence-Induced Stark Effects from an Arc Driven Shock Tube," (to be published), Proceedings of the 21st International Symposium on Shock Waves.

Johnson, III, J. A. and De Silva, U. P., "Supersonic Shear Flow: Reynolds Stresses and Turbulent Closure", Submitted to J. Phys. D.

Johnson, III, J. A., De Silva, U., Zhang, J. and Orou, J. C., "Evidence of Natural Closure in Compressible Turbulent Flow", J. Phys. D: Appl. Phys. 29 pp. 263-266, 1996.

Johnson, III, J. A., Hong, Y and Johnson, L. E., "A Chaotic Signature for Turbulent Dominent Modes in Collisional Plasmas", Mathematical and Experimental Development for Nonequilibrium Statistical Systems (ToBe Published), Editors: J. A. Johnson, III, 1996.

Johnson III, J.A., Johnson, L.E. and Liang, Z., "Chaotic Processes in Magnetized Turbulent Shock Waves", Shock Waves, Proceedings, Sendai Japan Vol. II, Editors: K.Takayama, Springer-Verlag, 1992, pp 1307-1312.

Johnson III, J.A., Johnson, L.E. and Zhang, J., "An Attractor-Driven Approximation for Turbulent Burst Dynamics in a Supersonic Free Shear Layer", Shock Wave @ Marseille I, Editors: R. Burn and L.Z. Dumitrescu, Springer Verlag, Berlin, 1995, pp 117-122.

Johnson III, J.A., Johnson, L.E. and Zhang, J., "Compressible Turbulent Flow in a Supersonic Free Shear Layer", AIAA Journal (To Be Published).

Johnson III, J.A., Johnson, L.E., Zhang, J. and Zhang, Y., "Preliminary Data on the Dynamics of Turbulent Shocklets", Advances in Compressible Turbulent Mixing ; Conf-8810234, Editors: W.P. Dannevik, A.C. Buckingham and C.E. Leith, 1992, pp 447-456.

Johnson, III, J. A., Menzolin, E. E., De Silva, U. and Hunte, F., "Turbulent Condensate Accretion in a Shock Tube's Expansion Fan", Submitted to Phys. of Fluids.

Johnson, III, J. A. and Orou, J. C., "Turbulent Enhancement of Second Viscosity in Flow", Physics of Fluids 6 pp.415, 1994.

Jones, H., "Developments in Multicenter Molecular Integrals Over STO's Using Expansions in Spherical Harmonics", Int. J. Quantum Chem. 417, 1994.

Jones, H., "Benchmark Values for Two-Center Coulomb Integrals Over Slater-Type Orbitals", Int. J. Quantum Chem. 21, 1993.

Jones, H. W., "Comprehensive Strategy for the Calculation of Overlap Integrals", Int. J. Quantum Chem 61 pp.881, 1997.

Jones, H.W. and Etemadi, B., "Accurate Ground State Calculations for H2+ Using Basis Sets of Atom-Centered Slater-Type Orbitals", Physical Review A47, 1993.

Jones, H. W. and Jain, J. L., "Evaluation of the Alpha-Function for Large Parameter Values", Int. J. Quantum Chem. Symp. 30 pp.45, 1996.

Joshi, C., Clayton, C.E., Marsh, K.A., Dyson, A., Everett, M., Lal, A., Leemans, W.P., Williams, R., T., T., Katsouleas , W.B., "Acceleration of Injected Electrons by the Plasma Beat Wave Accelerator", Conference Proceedings of the Advanced Accelerator Concepts Workshop, Port Jefferson, #279.

Kennedy, R.J., "The Structure of Iron Oxide, Nickel Oxide and Cobalt Oxide Thin Films Grown by Laser Ablation from Metal Targets", Submitted to Proceedings of the 44th Annual Denver X-Ray Conference , Colorado Springs.

Kennedy, R.J., "Growth of Iron Oxide, Nickel Oxide and Cobalt Oxide Thin Films by Laser Ablation from Metal Targets", IEEE Magnetics.

Kennedy, R.J., "Growth of Epitaxial Films of Iron Oxide, Nickel Oxide and Cobalt Oxide from Metal Targets by Laser Ablation", Materials Research Conference Q2.5, 1995.

Kennedy, R.J., "Growth of Ferrite Films by the Technique of Laser Ablation." , Bull. Am. Phy. Soc. BE-11, November 1994.

Kennedy, R., "Growth of Iron Oxide, Nickel Oxide and Cobalt Oxide Thin Films by Laser Ablation from Metal Targets", Digest of Intermag. 6, 1995.

Kennedy, R., "Growth of Epitaxial Films of Iron Oxide, Nickel Oxide, Cobalt Oxide, Strontium Hexaferrite, and Yttrium Iron Garnet by Laser Ablation", J. of Appl. Phys. 8 pp.4570

Krothapalli, A., Alvi, F. S., Washington, D. and King, C. J., "Aeroacoustic Characteristics of a Supersonic Diamond-Shaped Jet", AIAA Journal 34(8) pp.1562-1569, 1996.

Krothapalli, A. and Hsia, Y.C., "Discrete Tones Generated by a Supersonic Jet Ejector", Journal of Acoustical Society of America 99(2) pp.777-784, 1996.

Krothapalli, A. and Lourenco, L., "On the Accuracy of Velocity and Vorticity Measurements with PIV", Experiments in Fluids 18 pp.411-418, 1995.

Krothapalli, A., Mungal, M. G. and Lourenco, L. M., "Visualization Velocity and Vorticity Fields", Combustion Science and Technology 106 pp.239-265., 1995.

Krothapalli, A., Soderman, P.T., Allen, C.S., Hayes, J.A., and Jaeger, S.M., "Effects of Flight on the Far-Field Noise of a Heated Supersonic Jet", AIAA Journal.

Krothapalli, A., Strykowski, P. J. and Jendoubi, S., "The Effect of Counterflow on the Development of Compressible Shear Layers", J. of Fluid Mechanics 308 pp.63-96, 1996.

Liang, Z., Johnson , L.E. and Johnson III, J.A., "Turbulent Magnetized Plasmas from Ionizing Shock Waves", Submitted to Physical Review E.

Lourenco, L. M. and Krothopalli, A., "Particle Image Velocimetry", Handbook of Fluid Dynamics & Fluid Machinery, Vol. 2, Editors: Fuchs and Schetz, John Wiley & Sons, 1996, pp 988-1012.

Lourenco, L., Shih, C. and Krothapalli, A., "Observations on the Near Wake of a Yawed Circular Cylinder", Laser Anemometry in Fluid Mechanics V, Editors: R.J. Adrian et al., Springer-Verlag, 1993.

Markiewicz, W.D., Vaghar, M.R., Dixon, I.R. and Garmestani, H., "Generalized Plane Strain Analysis of Solenoid Magnets", IEEE Transactions on Magnetics 30 pp.2233-2236, July 1994.

Markiewicz, D., Voleti, S.R., Chandra, N. and Murray, F.S., "Transverse Stress on Nb3Sn Conductors in High Field NMR Magnets", IEEE Transactions on Applied Superconductivity 3(1) pp.258-262, 1993.

Mukherjee, S., Ananth, C.R. and Chandra, N., "Effect of Matrix Viscoplasticity on Residual Stresses in MMCs: Computational and Experimental Analysis", Recent Advances in Constitutive Laws for Engineering Materials, Springer-Verlag, August 1995.

Mukherjee, S., Ananth, C.R. and Chandra, N., "Effect of Residual Stresses on the Interfacial Fracture Behavior of MMCs", Composites Science and Technology , 1996.

Mukherjee, S., Ananth, C.R. and Chandra , N., "Evaluation of Fracture Toughness of MMC Interfaces Using Thin-slice Push-out Tests", Scripta Materialia , 1996.

Mukherjee, S., Garmestani, H. and Chandra, N., "Experimental Investigation of Thermal Stresses in MMCs Using Backscattered Kikuchi Method", Scripta Metallurgica et Materialia 33 pp.93-99, February 1995.

Mungal, M.G., Lourenco, L. and Krothapalli, A., "Instantaneous Velocity Measurements in Laminar and Turbulent Premixed Flames Using On-Line PIV", Comb. Sci. & Tech. (To Be Published).

Murali, K. and Chandra, N., "Micromechanical Modeling of Superplastic Deformation", Acta Metallurgica et Materialia 5 pp.1783-1790, 1995.

Orou, J.C. and Johnson III, J.A., "Second Viscosity Enhancement in Turbulent Nonequilibrium Flow", Physics of Fluids A 6 pp.415, 1994.

Rama, S.C., Chandra, N. and Goforth, R.E., "Computational Process Modeling of Dynamically Recrystallizing Superplastic Materials", Numiform 92, Editors: Chenot, et.al., Balkema Publishers, 1992, pp 867-875.

Rama, S.C., Chandra, N. and Goforth, R.E., "Numerical Modeling of Superplastic Sheet Forming Processes for 3-D Configurations", Superplasticity and Superplastic Forming of Advanced Materials, Editors: T. Chandra et. al., TMS Publishers, 1993.

Ross, C., Krothapalli, A. and Lourenco, L.M., "An On-Line PIV Study of a Rectangular Supersonic Jet Ejector" AIAA Paper 94-3086, Submitted to Journal of Propulsion and Power.

Saha, B. C. and Weatherford, C. A., "Theoretical Rotational and Vibrational Cross Sections for Low Energy e+ + N2 Scattering", Proceedings of the Nineteenth International Conference on the Physics of Electronic and Atomic Collisions, Editors: J.B.A. Mitchell, J.W. Mitchell, J. W. McConkey and C.E. Brion. Whistler. British Columbia. 1995. pp 357.

Saha, B. C. and Weatherford, C. A., "Electron Capture from excited alkalies by H+ at low energies", Proceedings of the Fourth Conference on Current Trends in Computational Chemistry, Editors: J. Leszczynski, Vicksburg, MS, Nov., 1995, pp 97.

Shankar,, S. and Van Dommelen, L., "A New Diffusion Procedure for Vortex Methods", Journal of Computational Physics 127 pp.88-109, 1996.

Shankar, S. and Van Dommelen, L. L., "A new diffusion scheme in vortex methods for three-dimensional incompressible flows", 2nd International Workshop on Vortex Flows and Related Numerical Methods, Montreal, Canada. Aug. 20-24, 1995.

Shankar, S., Wang, S.-C. and Van Dommelen, L.L., "Simulating Diffusion In Vortex Methods Using a Vorticity Redistribution Technique", Forum on Vortex Methods for Engineering Applications, Albuquerque, NM. pp.105-124, Feb. 22-24, 1995.

Shih, C., Krothapalli, A. and Gogineni, S.P., "Experimental Observations of Instability Modes in a Rectangular Jet", AIAA Journal 30 pp.2388-2394, 1992.

Shih, C., Lourenco, L. and Krothapalli, A., "An Experimental Investigation of the Flow at Leading and Trailing Edges of a Pitching Airfoil", AIAA Journal (To Be Published).

Shih, C., Lourenco, L., Van Dommelen, L. and Krothapalli, A., "Unsteady Flow Past an Airfoil Pitching at a Constant Rate", AIAA Journal 30 pp.1153-1161, 1992.

Strykowski, P.J., Krothapalli, A. and Wishart, D., "The Enhancement of Mixing in High-Speed Heated Jets Using a Counterflowing Nozzle", AIAA Journal 31 pp.2033-2038, 1993.

Temkin, A. and Weatherford, C.A., "The (Non-Iterative) Partial Differential Equation Method: Application to Electron-Molecule Scattering", Computational Methods for Electron-Molecule Collisions, Editors: W.M. Huo and F.A. Gianturco, Plenum, NY, 1995, pp 191-212.

Townsley, T.A., Garmestani, H., Chandra, N. and Sabinash, C., "Residual Stress Development During Fabrication and Processing of Gamma-Titanium Based Composites", Submitted to Scripta Metallurgica.

Vaghar, R., Garmestani, H. and Markiewics, D., "Elastic Plastic Stress Analysis of Nb3Sn Superconducting Magnets", Journal of Applied Physics 80(n4) pp.2490-2500, 1996.

Van Dommelen, L., "Note on inviscid singularities and turbulence", Submitted to Journal of Fluid Mechanics.

Van Dommelen, L.L., "Lagrangian computation of 3D unsteady separation", Int'l. Workshop on Advances in Analytical Methods in Aerodynamics, Miedzyzdroje, Poland. July 12-14, 1993.

Van Dommelen, L. L. and Shankar, S., "Two Counter-Rotating Diffusing Vortices", Physics of Fluids 7 pp.808-819, 1995.

Van Dommelen, L. L. and Shankar, S., "Aerodynamic forces are not affected by initial separation", Submitted to Physics of Fluids.

Van Dommelen, L.L. and Wand, S.-C., "Determining Unsteady 2D and 3D Boundary Layer Separation", Symposium on Aerodynamics and Aeroacoustics, Editors: K.Y. Fung, World Scientific Publishing, 1994, pp 187-206.

Voleti, S.R., Chandra, N. and Miller, J., "Global-local Analysis of Large-scale Composite Structures using Finite Element Methods", Computers & Structures 58 pp.453-464, 1995.

Voleti, S.R., Miller, J. and Chandra, N., "Structural Optimization of the Superconducting Outsert of a 45-T Hybrid Magnet", Cryogenicss , 1996.

Washington, D., Alvi, F.S., Strykowski, P.J. and Krothapalli, A., "Multi-Axis Thrust Vector Control of a Supersonic Jet using Counterflow", AIAA Journal 34(8) pp.1734-1736, 1996.

Weatherford, C.A. and Temkin, A., "Completion of a Hybrid Theory Calculation of the Pg Resonance in Electron-N2 Scattering", Physical Review A49 pp.2580, 1994.

Whitley, N., Krothapalli, A. and Van Dommelen, L., "A Determinate Model of Thrust Augmenting Ejectors", Theoretical and Computational Fluid Dynamics 8 pp.37-55, 1995.

Williams, R.L., Clayton, C.E., Joshi, C. and Katsouleas, T., "Studies of Classical Radiation Emission From Plasma Wave Undulators", IEEE Trans. Plasma Sci..

Williams, R.L. and Katsouleas, T., "Numerical Studies on the Ramped Density Plasma Lens", AIP Conference Proceedigns of the Advanced Accelerator Concepts Workshop, #279.

Wishart, D.P., Krothapalli, A. and Mungal, M.G., "Supersonic Jet Control via Point Disturbances Inside the Nozzle", AIAA Journal 31 pp.1340-1341, Nov. 7, 1993.

Xie, Z. and Chandra, N., "Application of GPS Tensors to Fiber-Reinforced Composites", Journal of Composite Materials 29 pp.1885-1907, 1995.

Xie, Z. and Chandra, N., "Application of Equation Reguluation Method to Multi-Phase Composites", International Journal of Non-linear Mechanics 28(6) pp.687-704, 1993.

Appendix B

Students in CeNNAs 1992-1996

Students in CeNNAs 1992 - 1996

#	Personal Statistics					Degrees Acquired						Post CeNNAS
	Name	Major	Minority	Sex	Citiz.	Bachelors Year	Bachelors Place	Masters Year	Masters Place	Ph.D. Year	Ph.D. Place	Pursuit
1	Alexis, Velose *	Physics	Y	F	PR	1993	CCNY					Atlanta, GA. Teacher of H. S. Physics
2	Ananth, C.	M.E.	N	M	PR			1996	Ga. Tech.	1995	FSU	Post Doc./FSU
3	Barber, Edward	M.E.	Y	M	Y	1994	FAMU	---	FAMU			
4	Bennett, Michael	Physics	Y	M	Y	1994	FAMU					Harvard, Student in Patent Law.
5	Bynum, Mark	Comp. Sci.	Y	M	Y				FSU			
6	Capistrano, F.	M.E.	Y	M	Y	1996	FAMU					Works for company.
7	Caumulaire, Frantz *	M.E.	Y	M	Y	1996	CCNY		FAMU			
8	Castallonos, Angello	Physics	Y	M	Y							
9	Chabi, Jean	Physics	Y	M	Y					1994	CCNY	NIST
10	Cidell, Jean	E. E.	Y	M	N					1994	Univ. du Benin	Professor, Université du Benin
11	DeSilva, Upal	M.E.	N	M	Y		FAMU					
12	Dike, Julie *	E.E.	Y	M	PR			1993	FSU	1996	FSU	Looking for job.
13	Edwards, Marvin	M.E.	Y	F	Y	1993	CCNY	1995	Stanford		Stanford	Working on dissertation.
14	Fearon, Stephanie	M.E.	Y	F	Y	1995	FAMU		FAMU			3-M, Applying to graduate school.
15	Foreman, Fred	M. E.	Y	M	Y	1996	FAMU					
16	Ford, Tavaris	Comp. Sci.	Y	M	Y	1996	FAMU		U. of Col.	1995	FAMU	FAMU-FSU College of Engineering
17	Fox, Niki	M.E.	Y	F	Y			---			FSU	General Elec.
18	Franklin, Tamika	M.E.	Y	F	Y		FAMU					
19	Gardner, Aric	Physics	Y	M	Y	1994	FAMU					
20	Gebre-Amlak, Helena	Physics	Y	F	PR		FAMU					Emery Univ., MD. Program.
21	Green, Alfred	M.E.	Y	M	Y		FAMU					
22	Haynes, Comas	M.E.	Y	M	Y	1994	FAMU					
23	Hogan, David	M. E.	Y	M	Y	1995	FAMU		FAMU		M.I.T.	
24	Holland, Michael	M.E.	Y	M	Y	1996	FAMU		VA Tech			Changed major to Civil Engin.
25	Humphrey, Stephanie	E. E.	Y	F	Y	1995	FAMU					
26	Hunte, Frank	Physics	Y	M	Y	1996	FAMU		FAMU			
27	Ivory, Angella *	M. E.	Y	F	Y			1995	Vanderbilt			
28	Jackson, Andrew	Physics	Y	M	Y	1994	FAMU					Working in industry.
29	Jackson, Jay	Physics	Y	M	Y	1994	FAMU	1996	FAMU			U.S.Army, Fulfilling ROTC commitment
30	Jenkins, Derell	M. E.	Y	M	Y	1995	FAMU					S. Africa, teaching Physics in technical school.
31	Johnson, Donald	M. E.	Y	M	Y	1995	FAMU		U. of MN.			Working in industry.
32	Jones, Major	M.E.	Y	M	Y	---	FAMU	1993	FAMU			Works for Lockeed.

Appendix C

CeNNAs Leveraged Funding

Leveraged Funds by Researchers 1992 - 1996

Source	Amount	Duration	Researchers
AFOSR	$109,952	7/92 - 7/93	Krothapalli
AFOSR	$57,265	1/94 - 1/95	Krothapalli
AFOSR	$241,000	10/92 - 9/95	Krothapalli
AFOSR	$440,000	1995	Kennedy
AFPSR	$69,915	6/96 - 5/97	Chandra
Army	$250,000	1/94 - 1/99	Weatherford
Army	$180,000	9/94 - 9/95	Williams
Boeing	$99,971	10/94 - 12/95	Chandra
DOE	$225,000	9/94 - 12/95	Johnson
DOE	$240,000	9/94 - 9/97	Johnson
FL, Dept. of Transp.	$50,000	12/95 - 12/96	Garmestani
Hewlette Packard	$51,035	1993	Kennedy
Lockheed	$44,985	7/93 - 6/95	Chandra
McDonnell-Douglas	$35,000	1992 - 12/95	Chandra
McDonnell-Douglas	$20,011	1/93 - 12/95	Chandra
McDonnell-Douglas	$100,000	12/94 - 12/97	Johnson
McDonnell-Douglas	$39,581	10/92 - 11/93	Krothapalli
McDonnell-Douglas	$75,665	4/95 - 12/96	Krothapalli
NASA	$123,992	10/94 - 4/95	Krothapalli
NASA Hq.	$50,000	1/92 - 1/93	Krothapalli
NASA, Ames	$50,000	5/94 - 5/95	Johnson
NASA, Ames	$240,000	9/94 - 9/97	Johnson
NASA, Ames	$103,947	8/93 - 10/94	Krothapalli
NASA, Ames	$60,358	10/94 - 9/96	Krothapalli
NASA, Langley	$75,000	4/93 - 7/94	Krothapalli
NASA, Langley	$49,982	11/95 - 9/96	Krothapalli
NASA/FSGC	$31,000	1994 -1996	Kennedy
Navy	$1,100,000	1/94 - 1/97	Weatherford
NHMFL	$35,000	9/94 - 9/95	Garmestani
NSF	$500,000	9/95 - 9/97	Ammons
ONR	$103,000	1993	Kennedy
ONR	$225,000	1994	Kennedy
ONR	$168,000	1994	Kennedy
ONR	$1,346,653	1/92 - 12/97	Krothapalli
Funds from NASA	*$784,279*		
TOTAL	**$6,591,312**		