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Transition location can be a significant source of uncertainty in high-speed vehicle drag and heating predictions. Also, the efficacy of transition control depends largely on where transition is predicted. Because of facility noise, transition measurements in ground-test facilities are generally not reliable predictors of flight performance and we must rely on computational approaches for design for flight.The program at Arizona State University to investigate stability and transition of hypersonic boundary-layer flows has been ongoing for several years. In this final report we compile the significant theoretical and computational results from this program. The research has progressed through several logical steps with increasing complexity: Linear stability theory with the effects of chemistry and bow shock on a sharp circular cone at zero incidence with a PNS basic state. Examine 3-D effects on a sharp elliptic cone at zero incidence with a PNS basic state. Include nose bluntness (entropy layer and curved shock) plus nonequilibrium chemistry on a circular cone in the nonlinear Parabolized Stability Equations with a Navier-Stokes basic state. Provide a new crossflow Reynolds number including compressibility and wall-temperature effects for use in conceptual design.

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STABILITY AND TRANSITION OF HYPERSONIC BOUNDARY-LAYER FLOWS

AFOSR GRANT NUMBER F49620-98-1-0205

FINAL REPORT

To

Dr. Steven Walker
Air Force Office of Scientific Research
Bolling Air Force Base, DC

December 1998

Submitted By

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Abstract

The importance of transition and its effect on skin friction in subsonic vehicle drag has been investigated for many years. However, in high-speed flows, the prominence of transition in vehicle heating and drag is more uncertain, because of the small amount of flight experience we have. Clearly, though, transition location can be a significant source of uncertainty in vehicle drag and heating predictions. Also, the efficacy of transition control depends largely on where transition is predicted.

The high levels of noise present in conventional hypersonic ground-test facilities cause transition to occur earlier than in flight. Because of facility noise, the trend of tunnel data can even be opposite to that for flight. Clearly, transition measurements in ground-test facilities are generally not reliable predictors of flight performance and we must rely on computational approaches for design for flight.

The program at Arizona State University to investigate stability and transition of hypersonic boundary-layer flows has been ongoing for several years. In this final report we compile the significant theoretical and computational results from this program. The research has progressed through several logical steps with increasing complexity:

- Linear stability theory (LST) with the effects of chemistry and bow shock on a sharp circular cone at zero incidence with a Parabolized Navier-Stokes (PNS) basic state.
- Examine 3-D effects on a sharp elliptic cone at zero incidence with a PNS basic state.
- Include nose bluntness (entropy layer and curved shock) plus nonequilibrium chemistry on a circular cone in the nonlinear Parabolized Stability Equations (NPSE) with a Navier-Stokes (NS) basic state.
- Along the way, we also provided a new crossflow Reynolds number including compressibility and wall-temperature effects for use in conceptual design.

These steps are described in more detail in this final report and in the indicated references. The ultimate goal is a predictive capability of transition location and trends on a general hypersonic vehicle.

Introduction

The importance of transition and its effect on skin friction in subsonic vehicle drag has been investigated for many years. However, in high-speed flows, the prominence of transition in vehicle heating and drag is more uncertain, because of the small amount of flight experience we have. Clearly, though, transition location can be a significant source of uncertainty in vehicle drag and heating predictions. Also, the efficacy of transition control depends largely on where transition is predicted.

The high levels of noise present in conventional hypersonic ground-test facilities cause transition to occur earlier than in flight, e.g. [1]. Because of facility noise, the trend of tunnel data can even be opposite to that for flight. Clearly, transition measurements in ground-test facilities are generally not reliable predictors of flight performance and we must rely on computational approaches for design for flight.

The program at Arizona State University to investigate stability and transition of hypersonic boundary-layer flows has been ongoing for several years. In this final report we compile the significant theoretical and computational results from this program. The research has progressed through several logical steps with increasing complexity:

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These steps are described in more detail below. The ultimate goal is a predictive capability of transition location and trends on a general hypersonic vehicle.

Linear Stability Theory - Effects of Chemistry and Bow Shock

The paper by Mack [2] is the most complete description of compressible stability available anywhere. The linear stability analysis of high-speed boundary layers uncovers three major differences between it and the subsonic analysis: the presence of a generalized inflection-point, multiple acoustic modes, and the dominance of 3-D viscous disturbances. Linear stability solutions for hypersonic flows are further complicated for some of the following reasons: 1) At hypersonic speeds, the gas often cannot be modeled as perfect because the molecular species begin to dissociate due to aerodynamic heating. In fact, sometimes there are not enough intermolecular collisions to support local chemical equilibrium and a nonequilibrium-chemistry model must be used. 2) The bow shock is near the edge of the boundary layer and must be included in transition studies.

In our program [3], the stability of a shock layer in chemical nonequilibrium was analyzed for a sharp cone and results were compared with those assuming 1) local chemical equilibrium and 2) a perfect gas. The coordinate system for both the basic-state and stability analysis fit the body and bow shock as coordinate lines. This makes it easier to apply the linearized shock-jump conditions as the disturbance boundary conditions. At the surface of the cone, for the nonequilibrium calculations, the species mass fluxes were set to zero (noncatalytic wall), whereas for the equilibrium calculations the disturbances were assumed to be in chemical equilibrium. It is clear that the equilibrium and nonequilibrium solutions can differ significantly depending on the rates of the reactions relative to the time scales of convection and diffusion. For example, some of the equilibrium modes were determined to be supersonic modes, each of which was a superposition of incoming and outgoing amplified solutions in the inviscid region of the shock layer; no similar solutions were found for the nonequilibrium shock layer. The magnitudes of these modes oscillated with y in the inviscid region of the shock layer. This behavior is possible only because the shock layer has a finite thickness. They are also unlike Mack's higher modes (except for the second) in that the disturbance-pressure phase for all of these supersonic modes changed most across the inviscid region of the shock layer. (The disturbance-pressure phase change for Mack's higher modes occurs across the viscous region of the flow, i.e. the boundary layer.) In fact, the disturbance-pressure phase change for all of these supersonic modes through the boundary layer is comparable to that of Mack's second mode.

Another effect of the chemical reactions is to increase the size of the region of relative supersonic flow primarily by reducing the temperature in the boundary layer through endothermic reactions, increasing the density, and hence decreasing the speed of sound. This reduces the frequency of the higher modes; in particular, the most unstable one, the second mode. The higher modes in the reacting-gas cases are also more unstable relative to the corresponding perfect-gas modes. The first modes are, however, more stable.

Finally, the finite thickness of the shock layer has a significant effect on the first-mode solutions of all of the families. The effect on higher-mode, higher-frequency solutions does not seem to be as large as long as they are subsonic. This is perhaps what one would intuitively expect because the shock is likely "stiff" and hence difficult to perturb with smaller-wavelength, larger-wavenumber, higher-frequency disturbances. However, nonparallel effects are known to be large for first-mode solutions, and a complete study of the effects of the finite shock-layer thickness requires at least an NPSE solution [4].

Linear Stability Theory – Elliptic Cone

The current concept of a hypersonic vehicle includes a forebody which we next modelled more generally as a sharp cone with an elliptical cross-section instead of a circular cross-section. (The blunt nose is considered in the next section.) The boundary layers associated with this geometry are 3-D. Three-dimensional boundary layers are susceptible to crossflow instabilities, as well as streamwise instabilities [5]. In fact, these crossflow instabilities are often the dominant mechanisms responsible for transition.

A PNS code was written to investigate the 3-D boundary layer at zero angle-of-attack [6]. The flow of interest was a calorically perfect ideal gas at a freestream Mach number of 4. Cones of various cross-sectional aspect ratios were investigated. As demonstrated in

Figure 1, the wall streamlines follow a path from the major axis toward the minor axis. There appears a "ballooning" of the velocity boundary layer in the vicinity of the minor axis, created by a welling of low-momentum fluid convected by the crossflow velocity. This produces unstable, inflected velocity profiles near the centerline. From a stability consideration, transition is first expected in the minor-axis region, not in the crossflow-dominated region. These observations are consistent with those of Kimmel, e.g. [1].

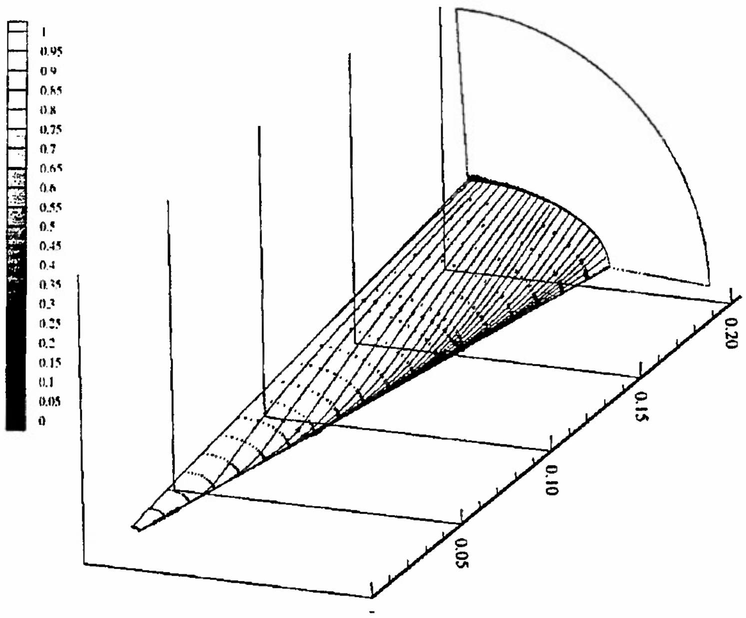
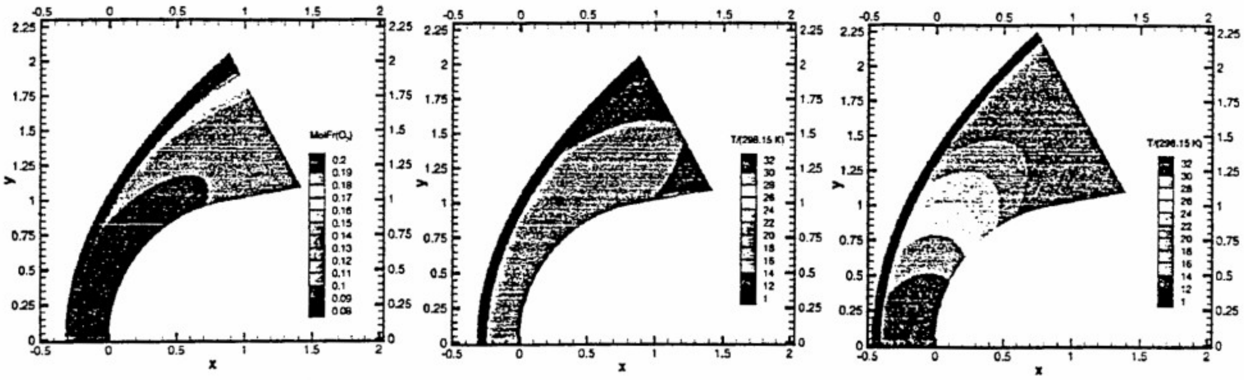


Figure 1: Wall streamlines for elliptic cone of cross-sectional aspect ratio 2, zero angle of attack, Mach number 4. Flow moves from major to minor axis.

Navier Stokes Basic State / Nonlinear Parabolized Stability Equations – Ongoing

The next and current step in our program was/is to investigate the nonequilibrium-chemistry flows on an elliptic cone with a blunt nose (including the entropy layer and curved shock). Based on our previous experience and recognizing the sensitivity of transition to even the smallest details of the basic state, a *well-resolved*, 3-D, steady, basic-state NS solution is necessary for this more complex geometry before subsequent transition studies can be attempted. However, there are several critical issues associated with the 3-D configuration that could and should be addressed by initially considering a 2-D geometry, such as a blunted circular cone at zero angle of attack. These problems include developing massively scalable parallel algorithms for structured-/unstructured-grid NS solvers and determining the appropriate chemistry model.

As of this report, the extent of physics modeled is chemical non-equilibrium, where it is assumed that one temperature describes the thermal state. The basic state is solved using an explicit finite-volume code, written for 2-D or axisymmetric flows. The inviscid terms are evaluated using a Roe upwinding scheme, with limiting terms and the viscous terms are evaluated using second-order finite differences. The chemistry model can be arbitrary, subject to availability of thermodynamic, reaction and inter-molecular potential data; currently, we have compiled this data for: N_2, N, NO, O, O_2, Ar, as well as for ideal air. A structured mesh is used initially for the sake of simplicity. One of the ultimate goals of this research is to rewrite the codes to use unstructured meshes. This will allow for the analysis of flow about more complex geometries.



Mole fraction of O_2 | Temperature (Real-gas effects) | Temperature (Ideal gas)

Figure 2: Contours for 10° blunted wedge. Inviscid case. Freestream conditions M_∞=12.5, T_∞=298.15K, p_∞=1 atm. Species model (N_2, N, NO, O, O_2).

One of the principles around which the basic-state code is written is the availability of a distributed memory parallel architecture. Such machines range from the do-it-yourself Beowulf cluster (as is in operation at ASU), to the Intel Paragon (as is used at Sandia). The code is written for scalable performance on such machines, meaning that the time required to run the code will scale (roughly) inversely with the number of processors available. The solution method is "cell-implicit" [7], meaning that the only terms evaluated implicitly are those involving the chemical reactions. This helps to remove problems associated with the stiffness of the system, without requiring a fully implicit treatment. This way, the parallel performance of the code is not compromised. As of the submission of this abstract, this basic-state code runs in parallel for inviscid cases. One such case is included among the figures, describing a five species flow (N_2, N, NO, O, O_2) around a blunted wedge at a freestream Mach number of 12.5. For this flow, there is considerable dissociation of oxygen, and lesser dissociation of nitrogen; see Figure 2. For comparison to show the importance of including real-gas effects, results from a calculation assuming ideal gas are also provided in Figure 2; for the ideal-gas case, the shock standoff distance and the post-shock temperatures are greater than those of the chemical-nonequilibrium case.

Once the basic state is completed, we shall model the transition process by NPSE spatial simulations with rate-chemistry effects on the blunt-nosed shape. In recent years the NPSE have become a popular approach to analyzing streamwise growth of disturbances in slowly varying shear layers, jets, and boundary layers. The NPSE include nonparallel and nonlinear effects ignored by linear stability theory [4,8]. Moreover, the NPSE have significantly less resource overhead associated with them compared with direct numerical simulations [4]. To date the NPSE have been applied to a variety of 2- and 3-D flow situations and are generally regarded as appropriate for convectively unstable flows [4,9]. In particular, for a far more complicated wall-bounded shear layer, we developed and validated the NPSE with wind-tunnel experiments at ASU on a swept airfoil [10-11]. The NPSE does an excellent job of capturing the details for little computational expense.

Transition Prediction - Correlation Parameters

This phase was an outgrowth of the above work in 3-D boundary layers. With the current interest in high-speed flight, there is also a keen desire to determine correlating parameters, based purely on basic-state profiles, that can be easily incorporated into existing basic-state codes and will predict transition location (or trends) for crossflow-dominated problems. To evaluate parameters quantifying stability characteristics, we examined the linear stability of the supersonic flow over a rotating cone at zero incidence. When compressibility and wall-temperature effects are included, a correlating parameter is found at transition [12]:

Quiet $R_{cf(new)} = 26.7 + 38.0\, W_{max}/U_e$ Noisy $R_{cf(new)} = 21.5 + 29.1 W_{max}/U_e$
for $2\% < W_{max}/U_e < 8\%$ where W_{max}/U_e is in percent

This result has been verified with available yawed-cone data (references available in [1]); see Figure 3. The new parameter is calculated solely from the basic-state profiles and, as such, it can aid in *conceptual (only)* transition prediction and design, including the evaluation of parameter trends, for 3-D boundary layers. Once a preliminary shape is selected, NPSE calculations are *strongly* urged.

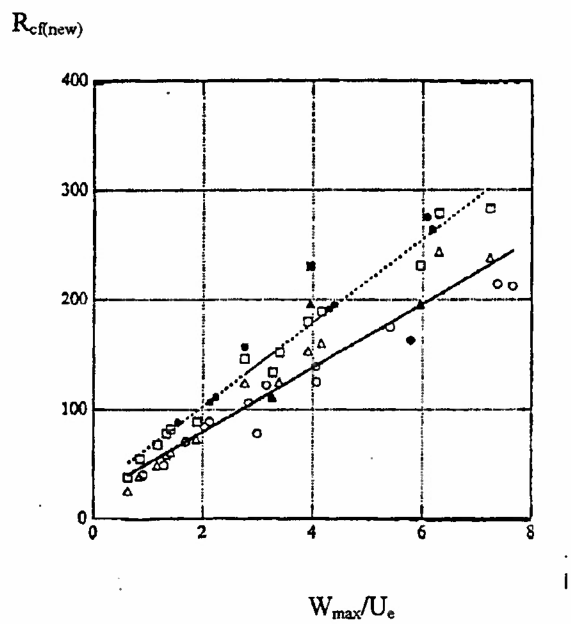


Figure 3: New crossflow Reynolds number (including compressibility and wall temperature) vs maximum crossflow velocity (solid line – noisy data; dashed line – quiet data) compared with experiments: King quiet ❑■;King noisy Δ▲;Stetson ○●;Holden ●

Acknowledgment/Disclaimer

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PH.D. STUDENTS

T. Haynes, "Nonlinear Stability and Saturation of Crossflow Vortices in Swept-Wing Boundary Layers," completed Fall 1996.

I. Lyttle, "Stability of Hypersonic Flow over an Elliptic Cone," expected Spring 1999.

PRINCIPAL INVESTIGATOR

The principal investigator for this work is Helen L. Reed. She received her Ph.D. in Engineering Mechanics in 1981 from Virginia Polytechnic Institute & State University and joined the faculty at Stanford University in September 1982. In the Fall of 1985, she began her appointment as Associate Professor at Arizona State University (ASU) and was promoted to Full Professor in July 1992. From August 1993-96, she served as Director of the ASU Aerospace Research Center and on December 1, 1994, she was named Associate Director of the ASU NASA Space Grant Program. She also worked at NASA-Langley in the Aeronautical Systems Division and at Sandia Laboratories in the Applied Mathematics Division.

Her research interests include computational fluid mechanics, boundary-layer transition, and flow control; low-cost space experimentation and satellite design; and enabling technologies for micro aerial vehicles. Recent work includes 1) ASUSat1, 10-pound satellite designed and built by students for low-cost Earth imagery, experimental verification of composite-material models, demonstration of student-designed systems, boards, and sensors, and provision of audio transponder for amateur radio operators; ASUSat1 will be launched in Sept. 1999 on the 1st Air Force OSP Space Launch Vehicle, 2) ASUSat2 – ThreeCornerSat Constellation, part of AFOSR/DARPA University Nanosatellite Program and joint effort among ASU, University of Colorado at Boulder, and New Mexico State University; our constellation will demonstrate stereo imaging, formation flying/ cellular-phone communications, innovative command/data handling, and micropropulsion. 3) Also student design and operation of human-powered moon buggy (Moon Devil) and micro aerial vehicles; Navier-Stokes simulations of boundary-layer receptivity to freestream sound; and Parabolized-Stability-Equation simulations of 3-D boundary layers.

She is a Fellow of the American Society of Mechanical Engineers (since 1997); an Associate Fellow of the American Institute of Aeronautics & Astronautics (since 1990); a Member of the U.S. National Transition Study Group (since 1984); the Originator of the Gallery of Fluid Motions of the American Physical Society (since 1983); a Member of the NASA Headquarters Aeronautics Advisory Committee (AAC), recently renamed Aeronautics and Space Transportation Technology Advisory Committee (ASTTAC) (1994-present); a Member of the NASA Independent Assessment Team for New Millennium Deep Space 3 and Space Interferometry Mission (SIM) (1997-present); acting Chair of the USRA Space Technology Council (1998-present); and the Associate Editor of the Annual Review of Fluid Mechanics (since 1986). She was a past Member of the National Academy of Sciences/National Research Council Aerodynamics Panel

(1990-92); a past Member of the NASA Federal Laboratory Review Task Force (1994-95); a past Member of the AIAA Fluid Dynamics Technical Committee (1984-89); a past Member of the Board of Directors of the Society of Engineering Science (1993-95); a past Member of the NASA Computational Aerosciences Review and Planning Team (1994); the past Chair of the Fluid Mechanics Committee of the Applied Mechanics Division of ASME (1993-96); a past Member of the Executive Committee of the American Physical Society/Division of Fluid Dynamics (1996-98); the first woman Member of the NATO/AGARD Fluid Dynamics Panel (1995-97); and a past Member of the NASA Headquarters AAC Task Force on University Strategy (1995-97). At ASU, she completed Leadership Academy in 1993-94; received the 1993-94 Undergraduate Teaching Excellence Award in the College of Engineering & Applied Sciences, the 1994-95 Outstanding Graduate Faculty Mentor Award from the Graduate College, the 1995 Bronze (ASU) President's Medal for Team Excellence, and the 1996 Distinguished Mentor of Women Award from the Faculty Women's Association; and was a member of the ASU team named as 1997 and 1998 Finalist in the Boeing Outstanding Educator Award competition.

Her resume is attached as Appendix A.

APPENDIX A: HELEN LOUISE REED

Director: ASUSat Lab and Moon Devil Team; Advisor: Micro Aerial Vehicle Team (MAVRIC)
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Personal Data: [redacted] PII Redacted

Education:

Ph.D., Engineering Mechanics, Virginia Polytechnic Institute & State University, December 1981
M.S., Engineering Mechanics, Virginia Polytechnic Institute & State University, June 1980
A.B. in Mathematics, Goucher College, May 1977

Professional Experience:

July 1992-Present	Professor, Mechanical & Aerospace Engineering, ASU
August 1993-August 1996	Director, Aerospace Research Center (ARC), Arizona State University (ASU)
September 1991-June 1992	Associate Professor, Institute of Fluid Sciences, Tohoku University, Sendai, Japan
August 1985-June 1992	Associate Professor, Mechanical & Aerospace Engineering, ASU
September 1982-August 1985	Assistant Professor, Mechanical Engineering, Stanford University
June 1977-December 1981	Aerospace Technologist, NASA/Langley Research Center

Awards and Recognitions:

1996 & 98	"Best Overall Design", Moon Buggy Race, US Space & Rocket Center, Huntsville
1997 & 98	Member of ASU Team selected as Finalist for Boeing Outstanding Educator Award
1997	Fellow, American Society of Mechanical Engineers, July
1994, 95, & 97	1st Place in Student Competition at AIAA/USU Small Satellite Conference, Faculty Advisor
1997	Invited for Poster Session on Capitol Hill sponsored by Council on Undergraduate Research (ASUSat 1), April 10
1997	2nd in "Best Overall Design" (Moon Devil III), 4th Moon Buggy Race, US Space & Rocket Center, Huntsville
1997	Article (ASUSat 1), *PRISM* (from American Society of Engineering Education), April
1996	Cover story (ASUSat 1), *Graduating Engineer* (from Peterson's Magazine Group), Volume 18, Issue 1
1996	Distinguished Mentor of Women Award, Faculty Women's Association, ASU
1995	Bronze (ASU) President's Medal for Team Excellence
1994-95	Outstanding Faculty Graduate Mentor Award from the Graduate College, ASU
1993-94	Undergraduate Teaching Award from College of Engineering & Applied Sciences, ASU
1988-89	Professor of the Year, Pi Tau Sigma, ASU
1988	AIAA Excellence in Teaching Award, ASU
1991	Faculty Awards for Women in Science and Engineering, National Science Foundation
1984	Presidential Young Investigator (PYI) Award, National Science Foundation
1978	Outstanding Achievement Award from NASA/Langley Research Center
1976	Outstanding Summer Employee Award from NASA/Langley Research Center

Service:

Member, NASA Independent Assessment Team, New Millennium Deep Space 3 & Space Interferometry Mission, Nov. 1997-present
Acting Chair, USRA Space Technology Council, January 1999-present
Member, NASA Federal Laboratory Review Task Force, NASA Advisory Council (NAC), September 94-March 95
Member, NASA Aeronautics and Space Transportation Technology Advisory Committee (ASTTAC), 1997-1998
Member, NASA Aeronautics Advisory Committee (AAC), December 1994-1996
Member, NATO/AGARD Fluid Dynamics Panel, 1995-1998
Member, NASA Aeronautics Advisory Committee Task Force on University Strategy, 1995-1997
Member, Executive Committee of the American Physical Society/Division of Fluid Dynamics, 1996-1999
Member, Board of Directors of the Society of Engineering Science, 1993-1995
Member, U.S. National Transition Study Group, 1984-Present
Member, NSF PYI Workshop on U.S. Engineering, Mathematics, and Science Education for Year 2010 and Beyond, Nov. 4-6, 1990
Member, National Academy of Sciences/National Research Council Aerodynamics Panel which is a part of the Committee on Aeronautical Technologies of the Aeronautics and Space Engineering Board, November 1990-March 1992
Originator, Gallery of Fluid Motions of the American Physical Society/ Division of Fluid Dynamics, since 1983
Associate Editor, Annual Review of Fluid Mechanics, 1986-Present

Research Interests:

Computational fluid mechanics, boundary-layer transition, and flow control; nanosatellite design; and enabling technologies for micro aerial vehicles. Recent work includes 1) ASUSat1, 10-pound satellite designed by students for low-cost Earth imagery, experimental verification of composite-material models, demonstration of student-designed systems, boards, and sensors, and provision of audio transponder for amateur radio operators; to be launched Sept. 1999 on 1st Air Force OSP Space Launch Vehicle, 2) ASUSat2-Three CornerSat, part of AFOSR/DARPA Univ. Nanosatellite Program and joint effort among ASU, Univ. Colorado Boulder, New Mexico State; our constellation will demonstrate stereo imaging, formation flying/cellular-phone communications, innovative command/data handling, micropropulsion. 3) Also student design of human-powered moon buggy and micro aerial vehicles; Navier-Stokes simulations of boundary-layer receptivity to freestream sound; and Parabolized-Stability-Equation simulations of 3-D boundary layers.