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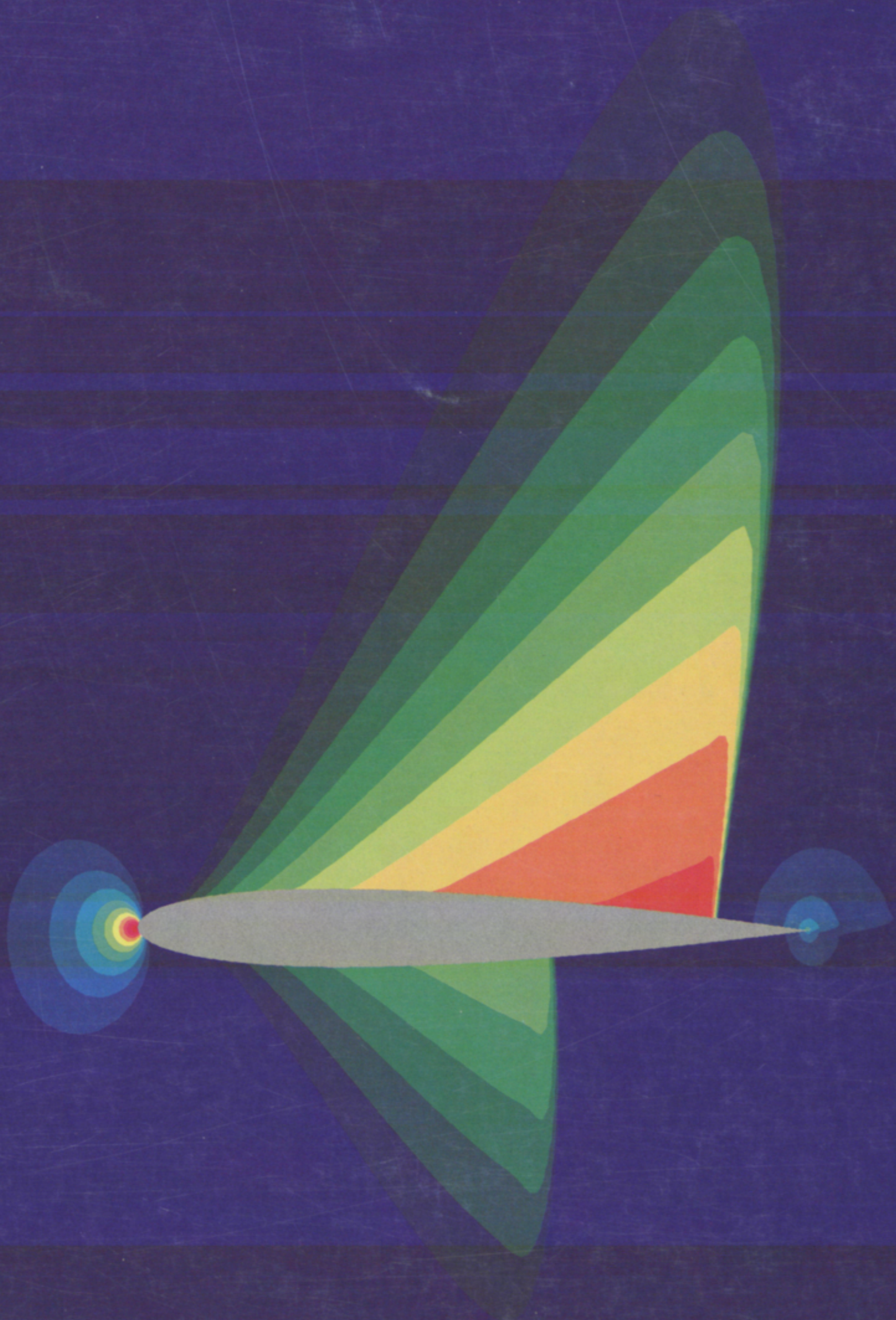

Aerospace Engineering at Cornell

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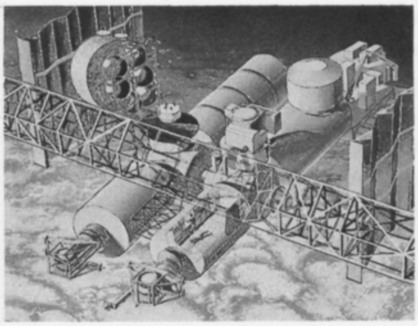

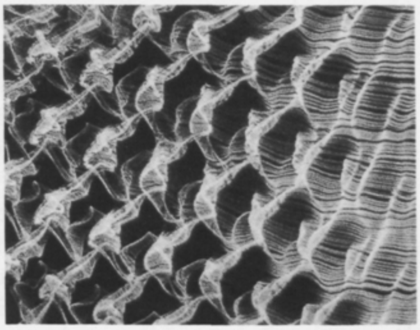

Cover: computed contours of constant Mach number for transonic flow of air past a wing section; image by D. A. Caughey

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AEROSPACE ENGINEERING AT CORNELL

by David A. Caughey

If the aircraft industry is in the doldrums, you wouldn't know it from the state of activity in aerospace engineering at Cornell. As the articles in this issue of the *Quarterly* illustrate, R&D in aerospace technology is vigorous and exciting and the future holds promise for expanding horizons—not only technologically but literally, in space around and beyond our Earth.

Of course, a relatively small research program such as Cornell's must focus on certain areas of a field that is as encompassing as aerospace engineering. The field covers four aspects of flight-vehicle performance—aerodynamics, propulsion, structures, and dynamics and control—as well as the systems aspects of working within the constraints imposed by each of these separate disciplines to design a workable vehicle. In Cornell's Sibley School of Mechanical and Aerospace Engineering, the principal emphases are on aerodynamics and the mechanical and thermal aspects of aerospace engineering, areas that have been the basis of Cornell's historical strength in aerospace engineering. Although less attention is given to structures and to dynamics and control, important programs relevant to flight structures are ongoing in civil and environmental engineering, in theoretical and applied mechanics, and, more recently, in the Sibley School itself.

The articles in this issue concern technologies that have significant applications to the aerodynamic design of aircraft, the design of more efficient, more powerful, and less-polluting engines for both aircraft and stationary power plants, the design of thrusters for attitude control and station-keeping of orbiting satellites, the behavior of the wakes of wings and bluff bodies, and fundamental technology important for understanding the behavior of rocket fuels and other liquids in the microgravity environment of earth orbit or deep space. These articles indicate the balance that exists between experimental investigation and theoretical study, with its increasing use of computational analysis. (The programs emphasizing computational work benefit greatly from the computing resources available at the Cornell National Supercomputer Facility.)

In addition, many of the aerospace engineering faculty members have applied their knowledge of fluid mechanics and aerodynamics to problems outside the traditional realm of the discipline. For example, research that is part of the Cornell Injection Molding Project contributes to the understanding of the flow of plastics in molds. Also in progress is work on automotive aerodynamics and on automotive emissions and alternative fuels.

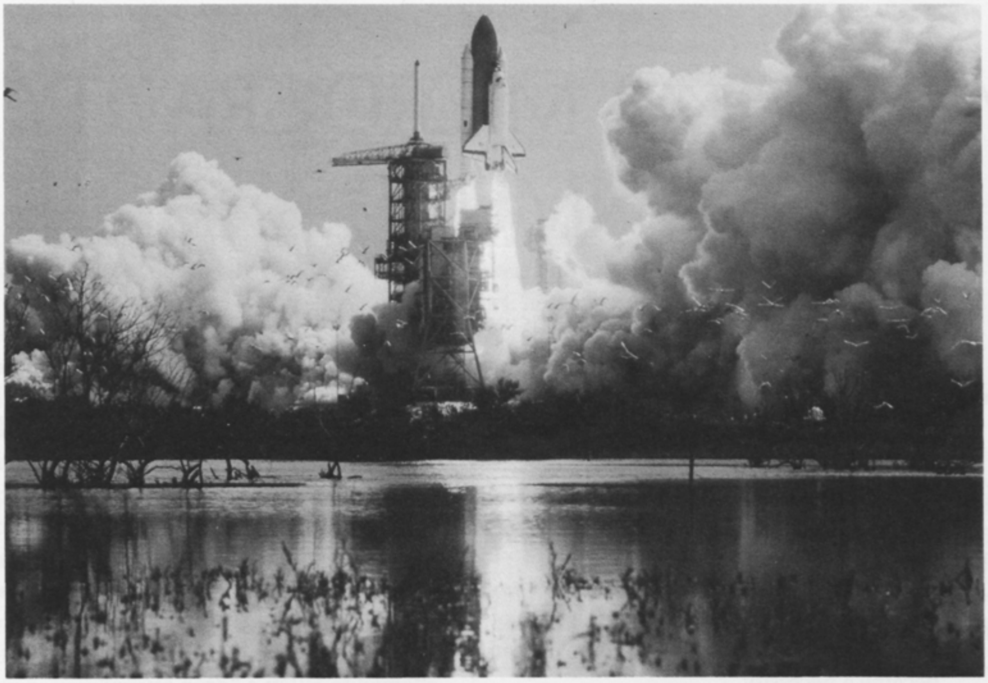
The Distinguished History of Aerospace Engineering at Cornell

The current program in aerospace engineering at Cornell is in the tradition of the long and distinguished history of the field at Cornell.

That history begins with the founding of the Graduate School of Aeronautical Engineering in 1946, with William R. Sears as its first director. (A fascinating personal recollection of the history of the school, written by Professor Edwin Resler, Jr., appeared in the Summer 1991 issue of this magazine.) In 1985 the William R. Sears Lectureship was established to honor Professor Sears' contributions to aerospace education at Cornell; this lectureship brings an outstanding aerospace scientist or engineer to campus each April for a week-long series of lectures on topics of current interest in fluid mechanics or aeronautics.

A two-year master's degree in aeronautical engineering was normally the first degree awarded by the old Aero School; graduates went on to important positions in industry or continued their studies toward a doctorate. The M.Aero.E. degree subsequently served as a model for the Master of Engineering degrees that have become an important element of the graduate programs in virtually all the engineering disciplines at Cornell. Research in the Aero School focused on problems in aerodynamics, aerothermochemistry, and magnetohydrodynamics.

The Aero School also served as the nucleus around which a number of other centers and departments in the college and university developed. The Center for Applied Mathematics was founded in 1963, with Sears as its first director. Research in magnetohydrodynamics and collaboration with researchers in electrical engineering led to the establishment of the Laboratory of Plasma Studies in 1967, with Peter L. Auer, a professor of aerospace engineering, as its first director. Faculty members who were specialists in aerospace engineering participated in the formation and development of the Department of Engineering Physics (now the School of Applied and Engineering Physics). More recently, faculty members in aerospace engineering, together with colleagues in space sciences and electrical engineering, succeeded in an effort to have Cornell designated a Space Grant University with funding from the National Aeronautics and Space Administration; the purpose of this program is to encourage greater interest and participation in the aerospace sciences, especially among undergradu-



The Space Shuttle Columbia lifts off from Cape Canaveral.

ates and high school students. (The article by Charles Williamson in this issue includes a description of research performed under the auspices of this program by Cornell undergraduate engineering students.)

In 1972 the Graduate School of Aerospace Engineering and the Sibley School of Mechanical Engineering were merged to form the Sibley School of Mechanical and Aerospace Engineering. Teaching and research in aerospace engineering have continued to be an important focus for many faculty members and graduate students in the school. Although degrees in aerospace engineering have been offered only at the graduate level at Cornell, undergraduate mechanical engineering students and others can take as electives a number of courses with an aerospace emphasis; this aerospace concentration continues to be one of the most popular among the record numbers of undergraduates in the Sibley School.

Prospects for the Future at Cornell and in the Industry

It is, of course, extremely risky to make any very specific predictions about the future of the aerospace industry at this time in our nation's history. The end of the cold war, at a time when the reduction of Federal deficits and the need for major social reform are perceived as important priorities, suggests the need for a permanent restructuring of the defense industry. Historically, cutbacks in activity in the defense sector have been buffered by increased activity in the commercial aircraft industry, but the current cutbacks in defense come at a time when commercial airlines, especially those in the United States, are showing poor profitability. It will probably be several years before a new quasi-equilibrium point is established in the aerospace industry.

Most analysts agree, however, that the long-range future for aerospace ventures remains bright. The impact on our everyday lives of past advances in aerospace technology has been enormous. From the reliability we have come to assume for transatlantic and transpacific airline travel to our routine, yet essentially invisible, reliance on telecommunications satellites for long-distance communications and navigational positioning, there is hardly a facet of our lives that does not benefit from advances in aerospace engineering. In the past, these advances have been spurred, at least in this country, by investment in the national defense. In the future, this investment will shift increasingly to projects associated with the exploration and utilization of space. The pace of projects associated with the exploration of space depends critically upon the national, or international, will and the extent to which these projects are seen as high priorities by the public. The commercial aircraft industry also appears headed for expansion and new enterprise. World airline passenger traffic is expected to double in the next decade, and the world commercial airline fleet is aging fast. Since the United States has in excess of a 70 per cent market share in both jet transport aircraft and jet engines, these trends bode extremely well for the commercial industry once the airlines figure out how to become more profitable.

Predicting the future of aerospace technology may be easier than trying to predict the future of the industry itself. Aerospace technology has found its way into innumerable commercial applications, ranging from the computer chips in high-speed modems for computer communications to the hydraulic controls on computer-controlled ride simulators in amusement parks.

I hope that a reading of the articles in this issue of the *Quarterly* conveys some of the excitement and promise of aerospace technology for the future.

EXPERIMENTS IN A MICROGRAVITY ENVIRONMENT

by C. Thomas Avedisian

"The creation of a space-like laboratory environment on earth became a necessity."

In space all bodies appear to have reduced weight, or even none at all. This unique feature assumed great importance when flight became possible in spacecraft. Aeronautics expanded into aerospace engineering and the compass of research was enlarged to include heat and mass transport processes associated with space flight. The creation of a space-like laboratory environment on earth became a necessity.

Besides its relevance to space studies, such an experimental facility can contribute to the understanding of physical processes on earth. In this article I will discuss the facility that has been built in our school, how it is used to study problems in the thermal and fluid sciences, and why the results provide valuable insights and information.

Gravity and Microgravity; Weight and Near-Weightlessness

The influence of gravity on all matter, whether solid, liquid, or gas, is to give it a property we call *weight.* The static and dynamic behavior of all phenomena, from the burning of a candle to the vibration of a beam, are affected.

An environment free of the effects of gravity conjures up images of astronauts in a space shuttle, tumbling around where there is no "up" or "down" and where pencils and papers, when released, do not drop to the floor but are left hanging in a state of levitation. But there are other ways to achieve this condition (see Figure 1). An airplane can climb steeply (at about 50°) and then dive, producing a state close to free fall near the apogee of its trajectory; a rocket can be launched into a suborbital trajectory; or a package that contains the experiment, equipment and all, can simply be allowed to fall in a "drop tower."

The principle of equivalence tells us how a drop tower works: If a box containing an experiment drops in a vacuum, the box and the experiment fall with the same acceleration, so that the experiment is stationary with respect to the box, even though both are accelerating in an inertial frame. Thus, they experience no gravity. Objects that fall through an atmosphere do not experience zero gravity because of air drag, but they do weigh considerably less than they do at rest on earth. The term microgravity is commonly applied to this condition of free fall through an atmosphere within a gravitational field.

One might wonder why anyone would want to create a microgravity environment and conduct experiments within it when it would be so much easier to do a computer simulation—to simply set the gravity vector to zero in a computer code. The answer is that there is a

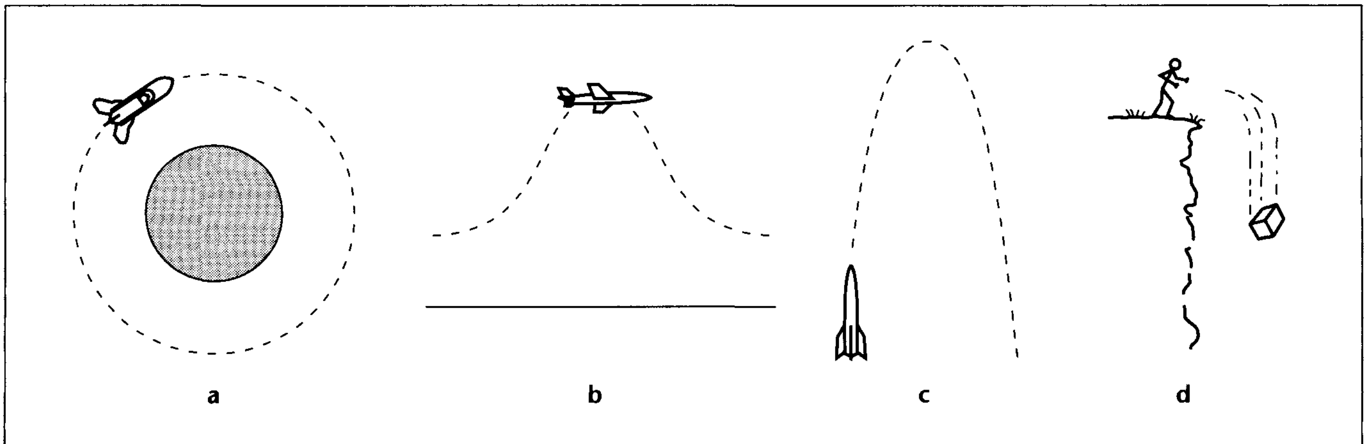


Figure 1. Four ways to overcome the effects of gravity. Free fall can be achieved for an unlimited time in an orbiting space shuttle (a), for about 25 seconds in a plane that climbs and then dives (b), for about 100 seconds at the peak of a rocket's trajectory (c), and for as much as 10 seconds in a falling body at the earth's surface (d).

shortage of the relevant data to test codes, and we are not always sure if the important physics in a problem is being included in an analysis. Testing in microgravity can show whether or not we are on the right track.

Creating a Laboratory That Falls Freely

Programs of experimentation in a microgravity environment are currently underway around the world, under sponsorship of agencies such as the National Aeronautics and Space Administration, the European Space Agency, and the Japan Space Utilization Promotion Center. The longest (and most expensive) periods of low gravity are achieved within the space shuttle, and the shortest (and cheapest) within drop towers.

At Cornell, we have created a microgravity environment by building a drop tower. This is essentially a shaft down which a box containing the "laboratory" is dropped. Such shafts can be of immense proportions. A drop tower in Bremen, Germany, rises to a height of 110 meters on the city's skyline. The NASA-Lewis 131-meter tower provides 5.2 seconds of microgravity, and the 500-meter drop tower installed by the Japan Microgravity Center in a converted mine shaft in Hokkaido provides up to 10 seconds of microgravity. The world's smallest drop tower is probably a 2-inch facility constructed by Sanjeev Chandra (Cornell Ph.D. '90, now at the University of Toronto).

Our facility (Figure 2) comprises a drop tower that extends 7.6 meters (25 feet) through two floors in Upson Hall, and a laboratory that is allowed to fall freely through this distance. The acceleration of gravity in this falling laboratory is little more than one one-hundred-thousandth that at the earth's surface. The time available to do an experiment—determined by the distance of the fall—is about 1.2 seconds.

Successful use of the drop tower involves careful design of the experiment. Camera, lighting, and the means to conduct the experiment must all fit into the drop package. The box and the instrumentation must be robust enough to withstand the shock of the fall. The experiment must be coordinated with the release of the box so as to take full advantage of the free-fall time. A way of supplying power to the on-board instrumentation during the fall must be provided. And the experiment must be carefully scaled so that it can be completed during the time allotted by the free fall.

Over the years, graduate and undergraduate students have solved these problems in their thesis and project research. A framed structure floating freely within an outer package, designed and constructed by undergraduate John Otto '90, serves as a shield that isolates the instrumentation from air drag. A multistrand cord hanging from the bottom of the package supplies power to the instrumentation—cameras, lighting, and electronics—on board the falling package. The package lands in a steel tank, 6 feet in diameter and 5 feet high, which contains air-tunneled foam to absorb the shock of deceleration.

Figure 2. The Cornell drop tower. The drop package, which falls through two floors in Upson Hall, provides about 1.2 seconds of free fall.

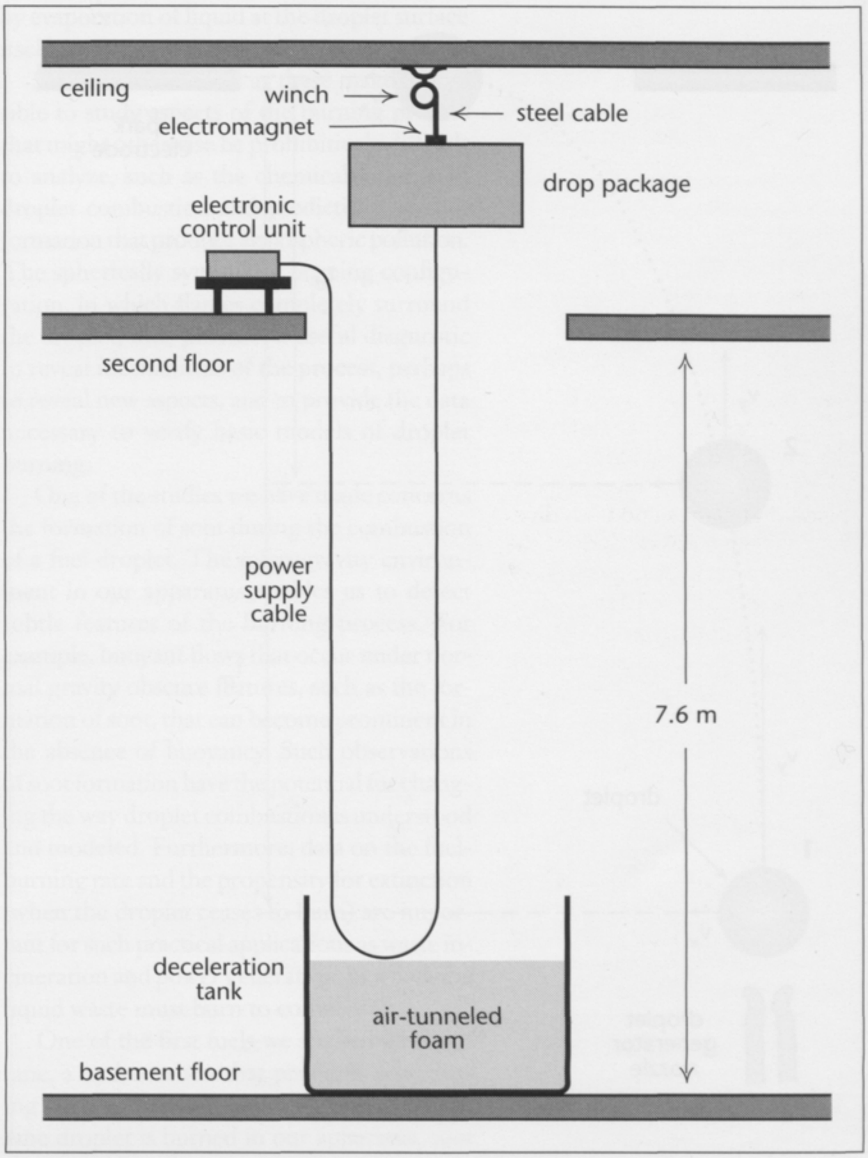
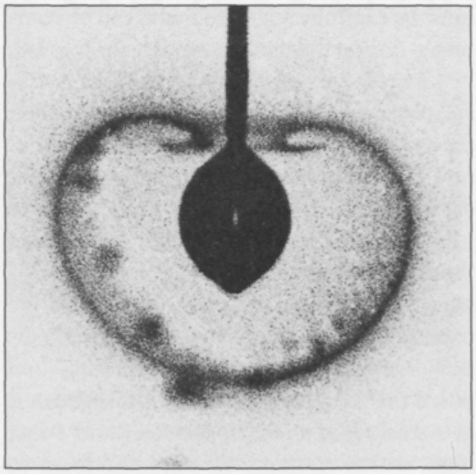


Figure 3. Combustion of a droplet suspended from a quartz fiber. In the absence of gravity, surface tension causes the droplet to move up the fiber. The photo and accompanying diagram show one of the burning patterns that has been observed.



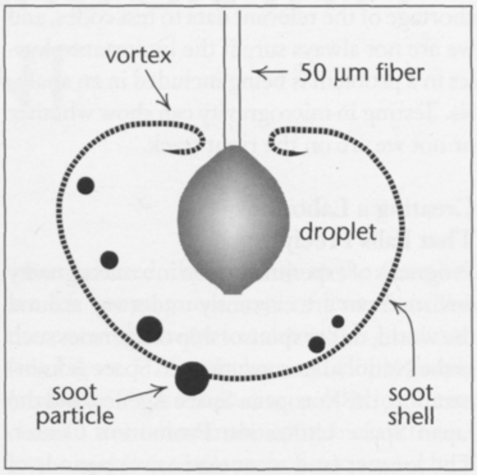
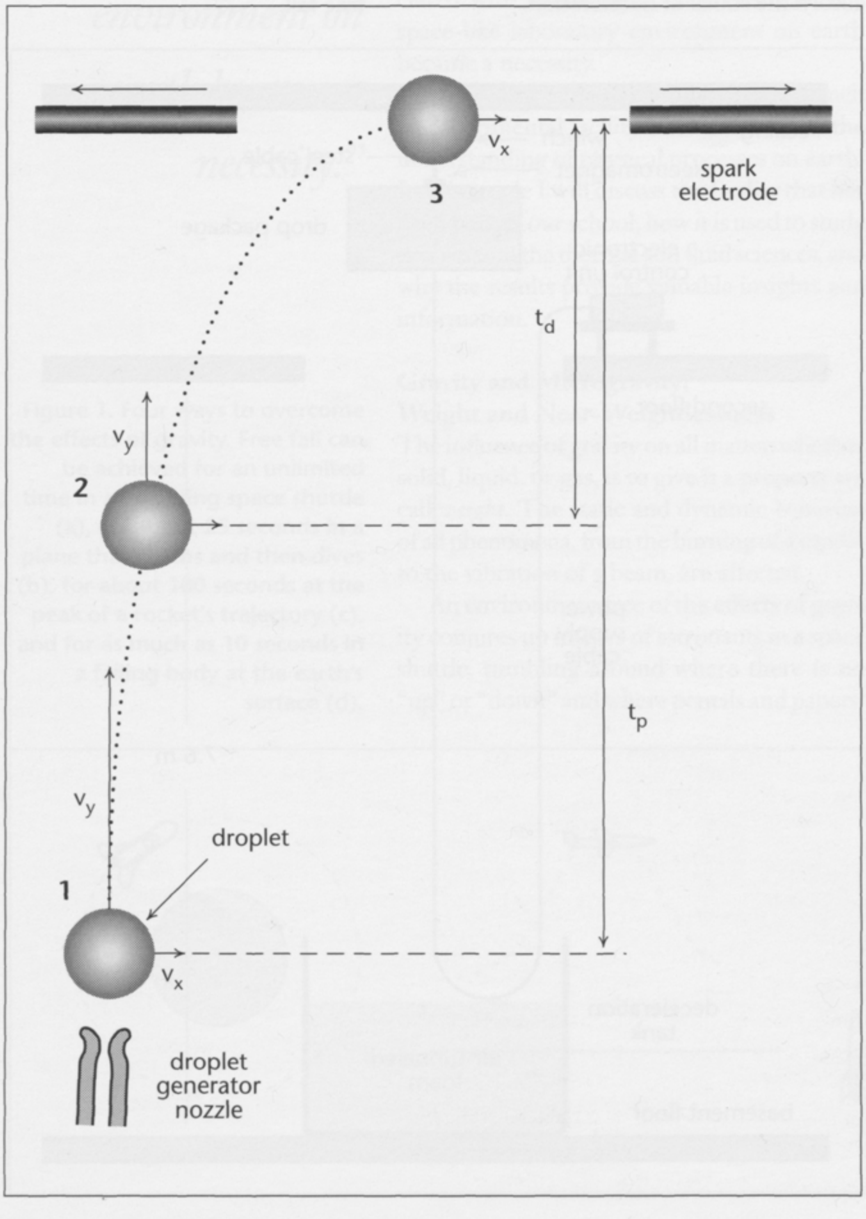


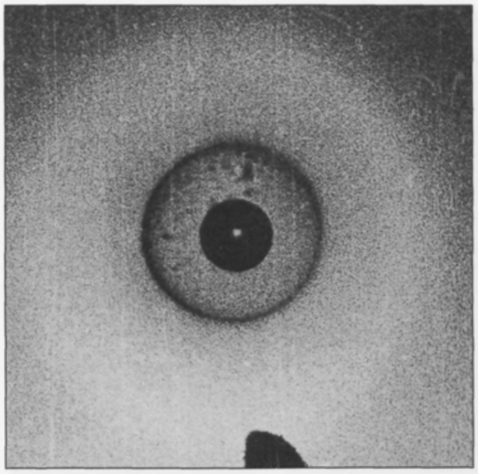
Figure 4. Droplet formation. The length of the arrows attached to the droplet show how the components of its velocity change as it moves toward the apex of its trajectory at position 3.



Studies of Droplet Combustion in Near-Zero Gravity

The combustion of droplets of fuel is one of the processes we are studying in the microgravity environment of our drop tower. Small spherical droplets are formed and ignited within the experimental box—the falling laboratory—and what happens is recorded. Our experiments have revealed some interesting aspects of the burning process not previously seen. These include unusual patterns of soot formation and an influence of initial droplet size on the burning process that is not accounted for by any current theory.

The experiment requires a droplet that moves at the same velocity as the package, camera, and surrounding atmosphere and that stays in the camera field. This is more difficult than it may seem. Any relative velocity can cause the droplet to move out of the camera's field of view. A simple solution would be to anchor the droplet to the falling package with a fiber, but then the anchor itself can influence the burning process (Figure 3). We have attempted to find a way to compensate for this influence by experimenting with heptane droplets suspended from quartz fibers of various small diameters. This revealed some unusual effects of the fiber support on the burning process. But our ultimate solution for creating a free-floating droplet is based on the familiar fact that an object thrown vertically will for a moment be completely motionless at the apex of its trajectory. In our design (Figure 4) the droplet is shot upward within a closed chamber and as it starts its downward flight, everything else, including the surrounding air, is dropped. If



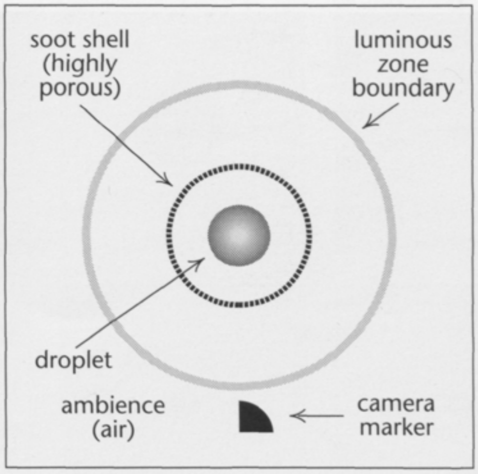


Figure 5. Combustion of an unanchored droplet in free fall. In this ideal circumstance, all features of the process are symmetrical in three dimensions.

this operation is successful, the droplet does not move (or moves very little) relative to the falling camera. Critical timing is required; it took three years before we achieved our first success. The problem was first solved by John Yang, a 1990 Ph.D. who is now at the National Institute of Standards and Technology.

Another problem that had to be solved was to set the droplet on fire and keep it burning long enough to record its complete combustion history in microgravity. Gregory Jackson, a 1993 Ph.D. who is now at Precision Combustion, Inc., designed an elaborate scheme that activates two sparks to ignite the droplet at its apex, and then instantly retracts the electrodes. We have found that for most fuel droplets with initial diameters smaller than 0.8 millimeter, 1.2 seconds of free fall provides sufficient time to record the droplet burning features.

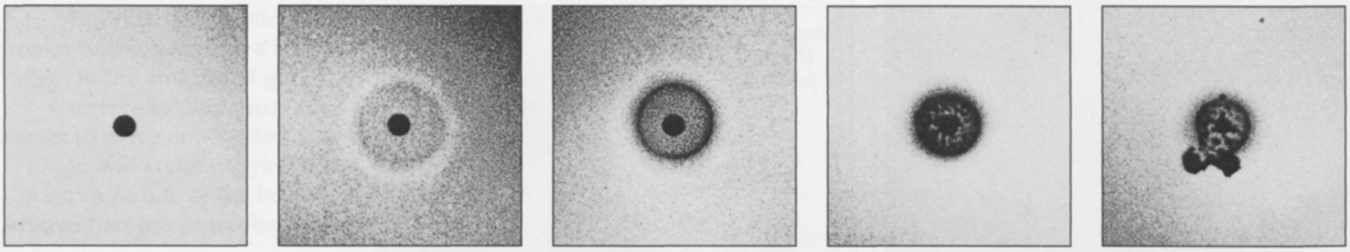
The Usefulness of Falling-Droplet Studies

There are really no practical applications in which spherically symmetric droplet burning is realized. Rather, the goal of the experiments is to simplify the otherwise complicated droplet-burning problem; in microgravity, fewer coordinates are needed to accurately determine the gas velocities, temperatures, and product-species distributions surrounding the burning droplet. The spherically symmetric configuration shown in Figure 5 is the archetypal configuration that is the goal of our experiments. When achieved, the velocity and temperature distribution surrounding the droplet will depend on just one coordinate, and the only gas motion that is created is caused by evaporation of liquid at the droplet surface itself.

Simplifications such as these make it possible to study aspects of the burning process that might otherwise be prohibitively difficult to analyze, such as the chemical kinetics of droplet combustion and predictions of soot formation that produce atmospheric pollution. The spherically symmetric burning configuration, in which flames completely surround the droplet, thus provides a useful diagnostic to reveal mechanisms of the process, perhaps to reveal new aspects, and to provide the data necessary to verify basic models of droplet burning.

One of the studies we have made concerns the formation of soot during the combustion of a fuel droplet. The microgravity environment in our apparatus enables us to detect subtle features of the burning process. For example, buoyant flows that occur under normal gravity obscure features, such as the formation of soot, that can become prominent in the absence of buoyancy. Such observations of soot formation have the potential for changing the way droplet combustion is understood and modeled. Furthermore, data on the fuel-burning rate and the propensity for extinction (when the droplet ceases to burn) are important for such practical applications as waste incineration and power generation, in which the liquid waste must burn to completion.

One of the first fuels we studied was heptane, a hydrocarbon that produces soot during combustion. We found that when a heptane droplet is burned in our apparatus, soot



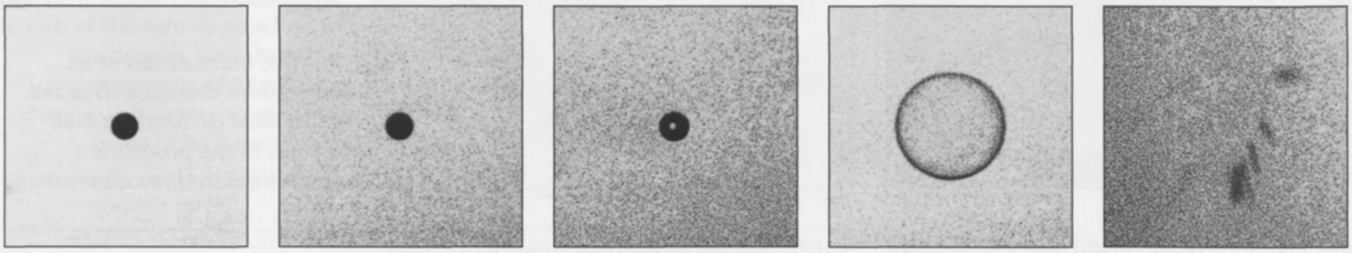


Figure 6a (top row). Development of a soot shell during combustion of a mixture of methanol and toluene.

Figure 6b (bottom row). Combustion of a mixture of methanol and docecanol. A wide difference in the boiling points causes a bubble to form in the droplet, which then swells and pops like a baloon.

collects in the form of a dark, nearly spherical shell around the droplet. This shell structure was studied by Gregory Jackson, who reasoned that a spherical shell forms because of a balance of forces on the particles. The development of this soot shell is illustrated in Figure 6a for a mixture of methanol and toluene (a system that was studied as a possible means of

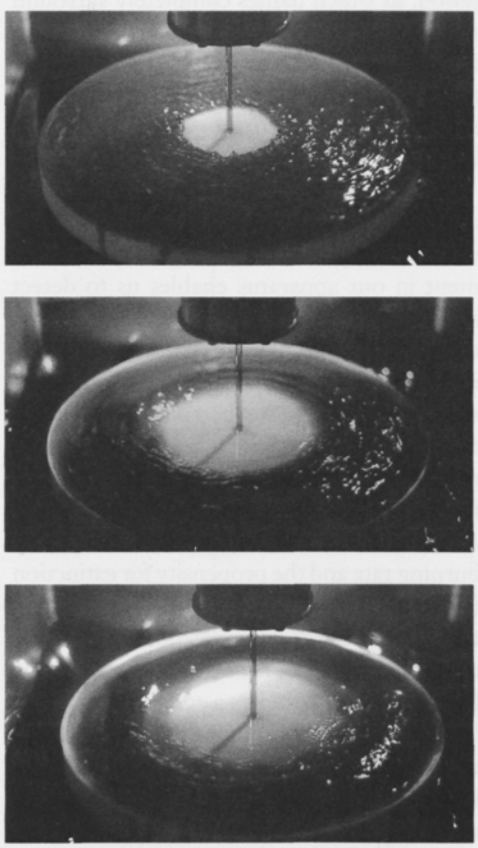


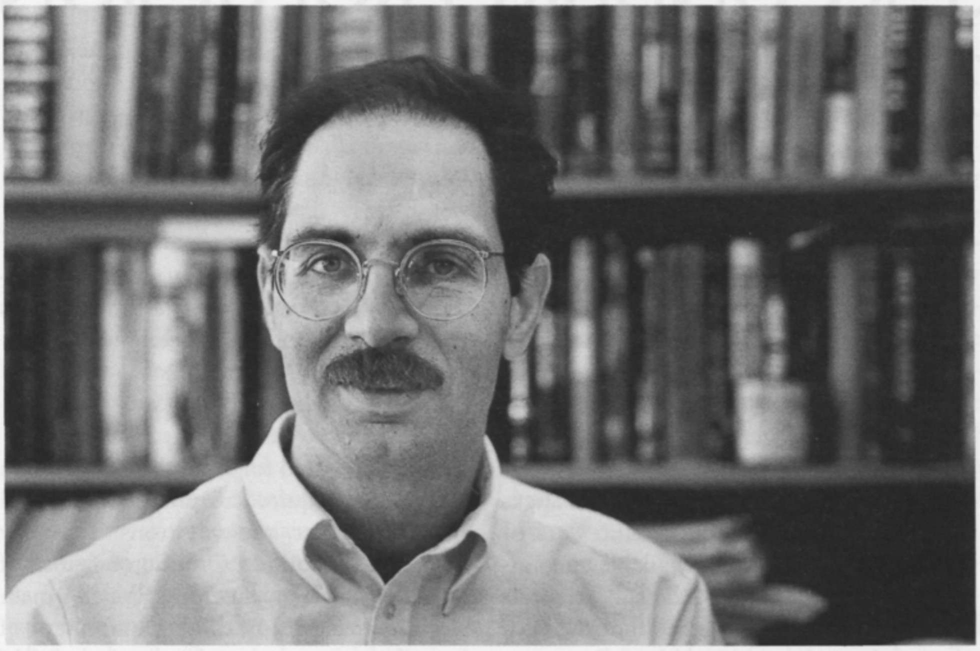
Figure 7.The hydraulic jump in microgravity. Water hitting the center of the plate spreads rapidly (light area) to the point of the jump. As the effect of gravity diminishes (top to bottom), the location of the jump moves out from the point of impingement.

controlling soot). Other fuel blends with differing properties have also been studied in microgravity. For example, John Yang found that blends such as methanol and dodecanol, which have very different boiling points, can lead to an explosion of the droplet during combustion, rather like a balloon popping (Figure 6b). This phenomenon, too, could figure in pollution control if it could be induced during the combustion process, because the smaller droplets produced by the explosion mix better with the surrounding air and burn more quickly, thus leading to more complete combustion.

Other Studies in Microgravity: Liquid Jets Impinging on Surfaces

Many phenomena other than the combustion of droplets can be studied in microgravity. For example, we have used our drop tower to study problems of a more purely fluid-mechanical nature. The behavior of a jet of water impinging on a surface in microgravity has been of special interest. The particular aspect of this problem we studied is the so-called hydraulic jump, which is a familiar occurrence at the kitchen sink: a circular bump may form a few inches outward from a water stream coming from the faucet and striking the sink. The practical importance of this phenomenon lies in the greatly lowered fluid velocity just downstream of the jump; reductions in heat transport may be expected in this region.

The radius of the jump is determined primarily by the fluid velocity and gravity. The



> *"Combustion is only one of the processes that can be better understood by eliminating gravity as an effect."*

expectation is that lowering the gravity will increase the radius of the jump, and that in *zero* gravity the jump will have an infinite radius and completely disappear. This hypothesis was tested by undergraduate Jean-Paul Davis '92 as a part of an independent study project. Using the drop tower, he recorded the evolution of a hydraulic jump. The results (Figure 7) provide strong evidence that the hydraulic jump does move outward in the transition from normal gravity to microgravity, for the diameter of the hydraulic jump increases as gravity is reduced, just as predicted.

The Significance of Experimental Work Carried Out in Microgravity

Among the current research priorities of aerospace engineering is the study of physical processes in space-like environments, as demonstrated by the experiments I have discussed. Combustion is only one of the processes that can be better understood by eliminating gravity as an effect. Other phenomena such as buoyancy-driven convection, sedimentation, and crystal growth also involve gravity, and studying them in a microgravity environment may yield unexpected insights.

Microgravity experiments that require a relatively long time must be conducted aboard a space shuttle, or the planned space station, when it is completed. But effects that take place within a few seconds can be observed more inexpensively in drop towers such as the one we have constructed at Cornell. Benefits from the knowledge gained in such experiments may be applied on earth as well as in space.

C. Thomas Avedisian is a professor in the Sibley School of Mechanical and Aerospace Engineering. He has been on the faculty since receiving the doctorate from Princeton University in 1980. A talented experimentalist whose research involves the study of heat transfer and combustion at small dimensions, he won a Presidential Young Investigator Award from the National Science Foundation in 1985. He and his students have also won several awards for their work: a Gallery of Fluid Motion Prize from the Fluid Dynamics Division of the American Physical Society in 1989 for photographs showing the impact of droplets on a surface; a best-paper award from the American Institute of Aeronautics and Astronautics (AIAA) for a paper on droplet combustion in microgravity; and a "picture gallery" award from the Institute of Liquid Atomization and Spray Systems in 1993 for photographs of droplet combustion. Avedisian is a fellow of the American Society of Mechanical Engineers and a member of Sigma Xi, Tau Beta Pi, AIAA, and the Combustion Institute.

MODELING SECONDARY PROPULSION SYSTEMS FOR SPACECRAFT

by Iain D. Boyd

"Improving the efficiency of secondary propulsion systems is a major objective."

A satellite orbiting around the earth would eventually fall out of its orbit and burn up in the atmosphere if it were not for the corrective firing of small rockets carried on board.

In fact, all spacecraft rely on small rockets, which together constitute the secondary propulsion system, to produce changes in orbit or orientation. On satellites, ten or more of these rockets are available to counteract the drag that the atmosphere exerts even at an altitude of several hundred kilometers above the earth's surface. On reconnaissance satellites, they are also used to effect orbital transfer. On space platforms such as the Russians' Mir and NASA's Space Station Freedom, they are needed for docking maneuvers.

The importance of the secondary propulsion system to overall spacecraft design becomes clear from an analysis of the mass budget. For most satellites, the fuel required for secondary propulsion takes up at least 30 percent and as much as 70 percent of the total satellite mass. It is a highly significant cost factor in the multi-billion-dollar industry of launching and operating satellites. Improving the efficiency of secondary propulsion systems is a major objective.

Our research group at Cornell is developing modeling techniques to facilitate the design of secondary propulsion devices. Up to now, research and development has relied mostly on experiment. Simple designs have been tested in the laboratory and implemented on spacecraft—a slow and expensive procedure. The alternative—numerical simulation—has been hampered by the lack of accurate numerical tools for modeling the rocket flows. In an ongoing research program sponsored mainly by the NASA Lewis Research Center in Cleveland, Ohio, we are developing and applying an accurate numerical method for modeling the flow in spacecraft secondary propulsion systems. In this article I will briefly discuss this program and its significance.

Types of Rockets for Secondary Propulsion Systems

The rockets used for secondary propulsion are usually required to produce low-level thrust—at most, a few newtons. This may be compared to the 1.7 million newtons of thrust produced by the Space Shuttle's main engine during liftoff. The requirement of low thrust means that the physical size of the rockets must be very small. Also, they must operate under conditions greatly different from those experienced by the primary rockets: the pressures and densities encountered in the flow through the small rockets are much smaller. As we shall see, these features present special difficulties in modeling the flow.

Many different designs for rockets that meet the requirements are currently available. Most of the satellites now flying are equipped with *resisto-jets* or *chemical rockets*, both of which are dependable but have low efficiency. In resisto-jets the gaseous propellant is heated with a resistance coil and then expanded rapidly to transfer the thermal energy into directed velocity, thus producing thrust. In chemical rockets, thermal energy is produced by chemical reactions that occur when fuel and oxidizer are mixed and burned.

Two other secondary-propulsion technologies are now receiving a great deal of attention. One is the *arcjet*, in which thermal energy is transferred to a gas as it flows through an arc discharge. The other is the *ion thruster*, in which the propellant is ionized and then accelerated to high speed in an electric field. This system has been developed and implemented successfully on a number of Russian spacecraft.

The Fluid Dynamics of Secondary Propulsion

The most effective way to achieve low thrust levels in most types of rockets (an exception is the ion thruster) is to use a small nozzle and a low gas-flow rate. For example, a typical resisto-jet producing a thrust level of 0.1 newton has a nozzle diameter at its exit of a few centimeters.

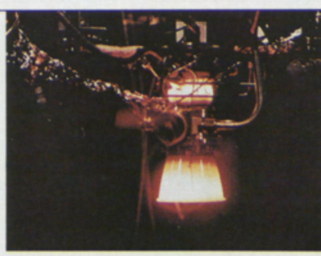
A useful parameter for characterizing the fluid dynamics of low-thrust rockets is the *Knudsen number:* the ratio of the mean distance between molecular collisions to a characteristic length. (For a Mach number of 1—when the flight speed equals the local speed of sound—the Knudsen number is approximately the reciprocal of the frequently used *Reynolds number.*) In general aerospace problems, such as flow of air over an aircraft, the Knudsen number is very much smaller than 1, perhaps 10^{-6}, so that the flow can be modeled using a macroscopic approach in which the fluid is treated as a continuum. This approach typically involves solution of the equations of fluid motion (such as the Euler or Navier-Stokes equations) using finite-difference techniques.

In the case of a satellite thruster, however, the low flow rate and small dimensions give a Reynolds number close to 1000 and thus a Knudsen number of about 10^{-3}, high enough that the discrete, microscopic nature of the molecules in the gas cannot be neglected. The number of collisions that occur in a fluid element are so small that the Navier-Stokes equations may not be valid from a physical standpoint. What is needed is a modeling technique that accounts for the finite number of collisions that occur at the flow conditions of the rocket. In addition, there may be further collision events—including chemical reactions, ionization, and relaxation of the internal energy modes of polyatomic gases—that must be taken into account; and because of the low collision rate, such processes may be in a state of nonequilibrium. All these conditions place a heavy demand on any numerical method.

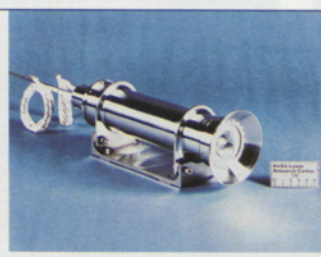
The technique used in high-Knudsen-number gas dynamics is called the *direct simulation Monte Carlo (DSMC)* method. It is based on a particle or Monte Carlo approach similar to other methods that are being applied in many scientific disciplines. In the DSMC method, the large number of molecules in the real gas flow are simulated in a computer by a much smaller number of model particles. These model particles have velocities and spatial coordinates. They travel through the flow domain and collide with other particles and with solid surfaces.

Total thrust provided by these secondary propulsion rockets ranges from 0.05 to 50 pounds. Chemical rockets and resistojets are used on current satellites. Arcjets, ion thrusters, and magnetoplasmadynamic rockets (MPDs) are under development by NASA, industry, and universities for future application. Research at Cornell has focused on resistojets and arcjets.

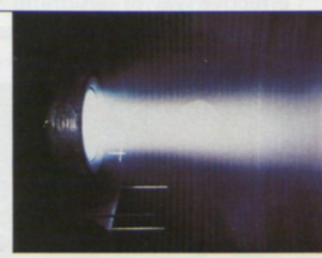
ROCKETDYNE H/O 25 LB THRUST ENGINE



BELL 50 LB THRUST H/O ENGINE FIRING

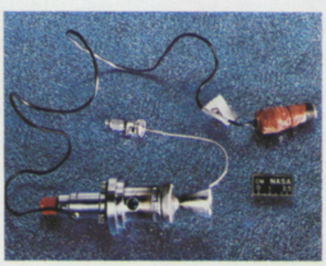


ROCKETDYNE/TECHNION SPACE STATION RESISTOJET 0.1 LB THRUST



HUGHES, 30 CM DIAM ION THRUSTERS

AEROJET 5 LB THRUST N_2O_4/MMH



ROCKET RESEARCH CO. 5 LB HYDRAZINE THRUSTER

ARCJET FIRING ON TEST STAND 0.05 LB THRUST

130 kW MPD

Key aspects of the method involve modeling these collision events. When two particles collide, they change their velocities, and may also change their internal energies (rotation, vibration) or undergo chemical reaction. When a particle collides with a surface, at least one of the velocity components will change, and surface chemical reactions may occur. All of these events can be simulated at some level using the DSMC method.

The DSMC method was developed in the 1960s, but its use had been restricted mainly to flows with a Knudsen number of about 0.1 or higher because of limitations of computer hardware. Now, however, modern computer architectures—vector supercomputers and scalable distributed memory multiprocessors—permit use of the DSMC technique for modeling flows at lower Knudsen numbers. It is being applied to problems in a growing number of scientific areas, including hypersonics, materials processing, nuclear physics, and micromachinery, as well as spacecraft secondary propulsion.

Applying the DSMC Method to Spacecraft Propulsion

The NASA Lewis Research Center, with which we are working, has been responsible for much of the development and testing in the United States of resisto-jets, chemical rockets, arcjets, and ion thrusters. The center has some of the most advanced experimental testing facilities for investigation of spacecraft propulsion. I will describe our use of the DSMC method to model a resisto-jet and an arcjet, both of which were designed at NASA Lewis.

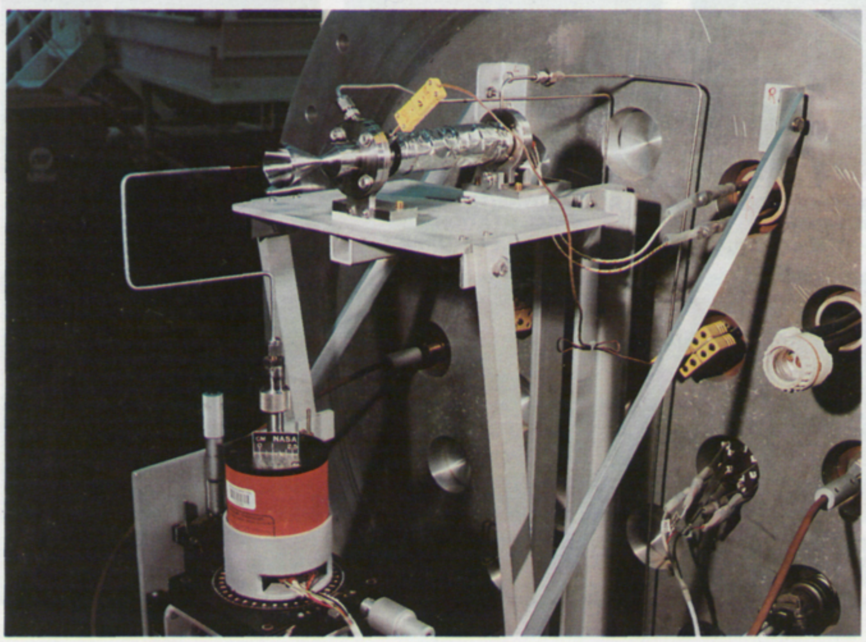
Nitrogen Resisto-Jet. Because of its simplicity, this was the first device looked at in the research program (which began as a joint project of NASA's Lewis and Ames Research Centers). The question put forward was: Could the DSMC technique accurately simulate the high-Knudsen-number fluid dynamics occurring in a typical resisto-jet?

A rocket using molecular nitrogen as propellant was designed and constructed at NASA Lewis. The thruster was installed in one of the vacuum test chambers at Lewis (see the photograph), and measurements were taken of pressure and flow angle in the jet expansion. The Reynolds number of the flow at the throat of the nozzle was 850.

Modeling of the flow was performed with a continuum approach entailing solution of the Navier-Stokes equations of viscous flow, and also with the DSMC technique. A comparison of the measured and calculated pressures at the nozzle exit plane of the resisto-jet is shown in Figure 1. At this low Reynolds number, viscous effects between the gas and the wall of the thruster are significant, as demonstrated in the figure by the large boundary layer that extends from the nozzle wall to a distance of about 1 centimeter from the nozzle axis. The comparison clearly demonstrates the accuracy and superiority of the DSMC modeling. Comparisons of DSMC results with experimental measurements taken further into the jet expansion also showed very good agreement.

The calculations are significant in several ways. They demonstrate that the continuum approach does fail under these flow conditions. They also illustrate the capabilities of the DSMC approach. The DSMC results shown in Figure 1 required four hours on a Cray Y/MP, demonstrating that DSMC calculations can be performed on current machines. In fact, the computer code that was developed is now being used at NASA.

The aim of that work is to optimize the geometry and flow conditions in resisto-jets to achieve better propulsive performance. Pre-



The resisto-jet thruster developed at NASA Lewis is shown with the vacuum chamber in which it is tested. This rocket, which uses molecular nitrogen as propellant, is one of the two main types now used for secondary propulsion on satellites. Numerical simulation techniques such as the those under development at Cornell would provide a faster and more effective way of designing the small rockets.

viously, these devices were designed using continuum methods and results. Because of the very high cost of spacecraft operation, the aerospace industry is interested in performance improvement of even a few percent, and it is expected that such a gain can be achieved through parametric studies employing the DSMC technique.

Hydrogen Arcjet. A second study involves the use of a 1-kW molecular hydrogen arcjet developed at NASA Lewis. The studies to date have considered flow without arc-ignition. DSMC results for this flow (which has a Reynolds number of 2800) show good agreement with experimental data obtained at Stanford University with use of laser diagnostic techniques.

A contour plot of number density predicted by the DSMC technique for the expansion of the low-density supersonic jet of hydrogen into the vacuum chamber is shown in Figure 2. A great deal of complicated fluid dynamics is occurring in this flow. A series of expansion and shock waves is generated in a thin band close to the plume centerline. Such structures are often seen at much higher Reynolds numbers; in this case the flow is affected by strong viscous and thermal nonequilibrium relaxation effects.

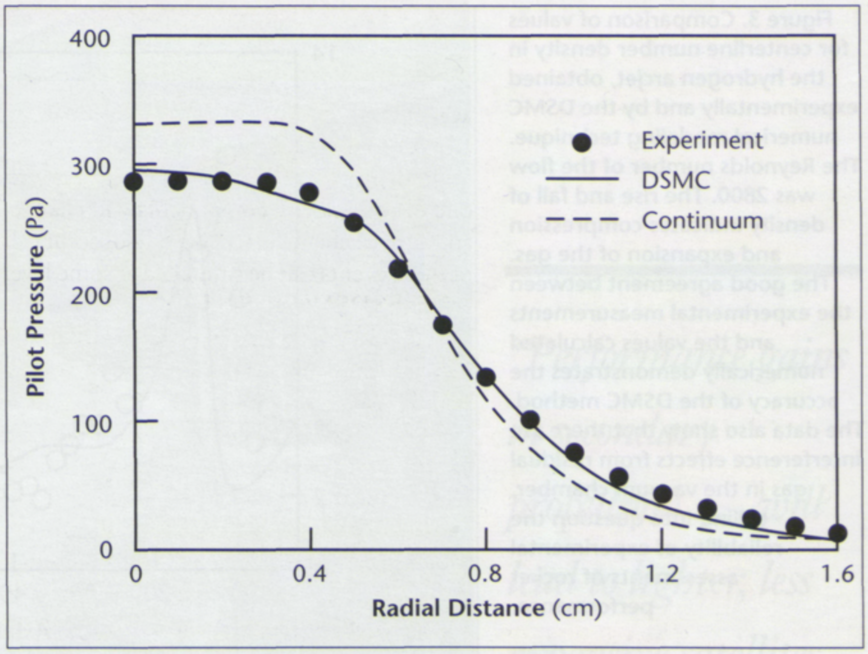


Figure 1. A comparison of techniques for modeling the flow in the nitrogen resisto-jet under study at Cornell and NASA Lewis. Experimental measurements of pressure are shown at the nozzle exit for various radial distances from the center of the nozzle to the wall (at 1.6 centimeters). The solid curve was obtained by the DSMC numerical technique developed at Cornell. The dashed curve was obtained by solving the Navier-Stokes equations of viscous flow.

The flow has a Reynolds number of 850, indicating a low gas density. Under such conditions, typical for secondary-propulsion rockets, the continuum assumptions of the Navier-Stokes equations are inadequate.

Figure 3 shows the comparison between our DSMC results and the experimental measurements of number density along the plume centerline that were obtained at Stanford. Note how the density falls and rises as the flow expands and compresses. The agreement between calculation and measurement is remarkable. Considering

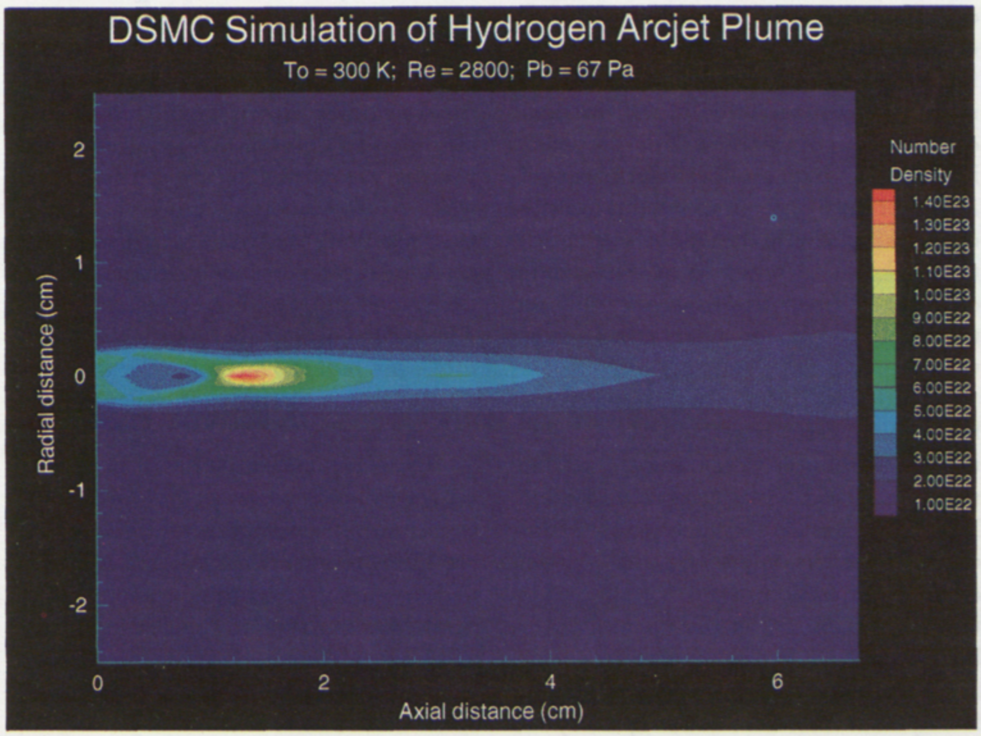
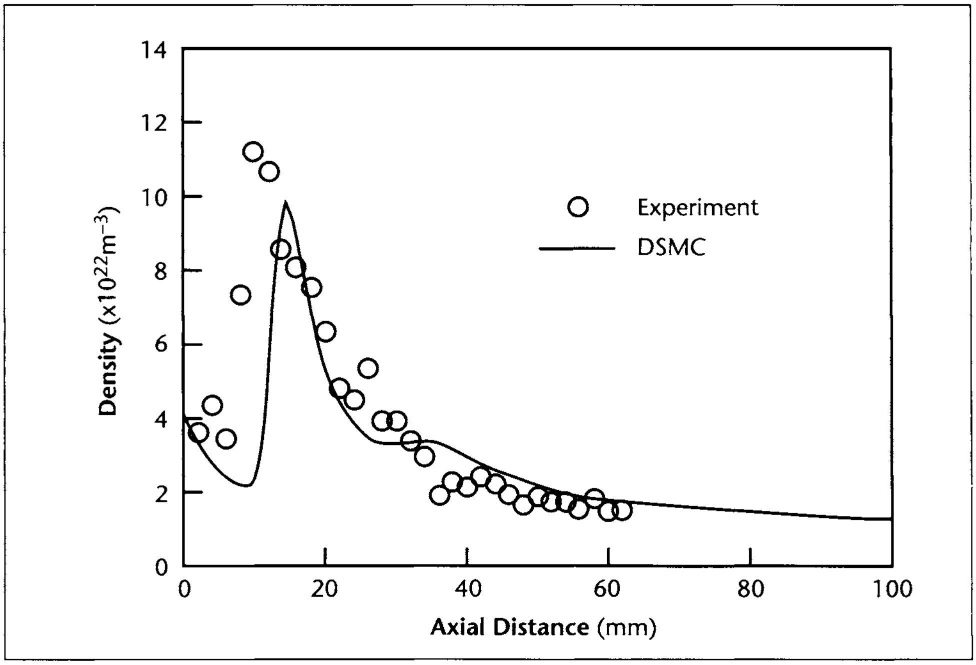


Figure 2. A contour plot of number density during expansion of a hydrogen arcjet into a vacuum chamber of finite pressure, as predicted by DSMC modeling. The stagnation temperature is 300 K, the Reynolds number is 2800, the vacuum tank pressure is 500 mTorr. The color scale shows number density in 10^{22} molecules of hydrogen per cubic meter.

Figure 3. Comparison of values for centerline number density in the hydrogen arcjet, obtained experimentally and by the DSMC numerical modeling technique. The Reynolds number of the flow was 2800. The rise and fall of density indicates compression and expansion of the gas. The good agreement between the experimental measurements and the values calculated numerically demonstrates the accuracy of the DSMC method. The data also show that there are interference effects from residual gas in the vacuum chamber, calling into question the reliability of experimental assessments of rocket performance.



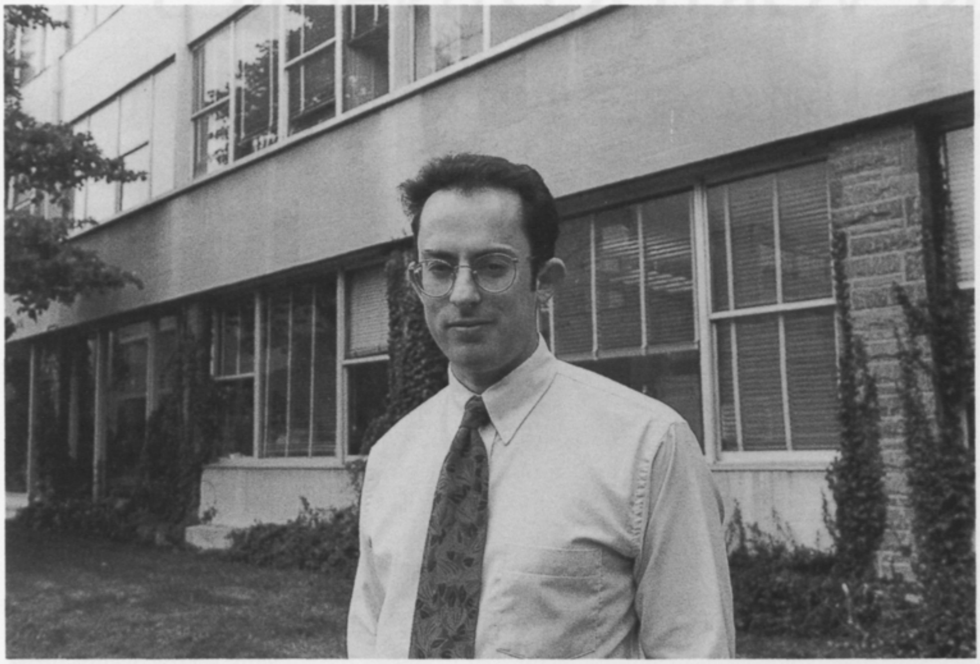
the degree of complexity in the flow field, this calculation represents a very powerful illustration of the usefulness of the DSMC technique for modeling these flows.

An important aspect of this study concerns the presence of background gas in vacuum chambers and the effect this has on experimental testing results. While spacecraft thrusters operate in the near-vacuum of space, testing in the laboratory is performed at a finite pressure because of limiting pumping capabilities; in the "vacuum" chamber a certain amount of the propellant lingers on and can produce interference effects. For the hydrogen arcjet, this interference was included in the DSMC calculation; the background pressure in the vacuum chamber was measured experimentally and this value used as a boundary condition for the computation.

A further implication of this study is that laboratory measurements are not necessarily dependable for predicting the performance of a secondary propulsion system. The DSMC results shown in Figure 3 indicate that there is only a very small portion of the jet expansion that is not affected by the background gas in the vacuum chamber. Any attempt to characterize the performance of the thruster in this experimental facility would therefore be corrupted by this interference. Since the development of secondary propulsion systems for spacecraft has been mainly experimental in nature, it is clearly extremely important to assess the interference effects of background gas on any measurements of the performance of a particular rocket. Indeed, the comparisons in Figure 3 illustrate the need for careful assessment and analysis of all such experimental investigations.

In future research we will simulate rocket flows in other experimental facilities. We also plan to develop the physical models necessary to simulate arc-ignited flows, which are considerably more challenging than the flows we have studied so far because of the occurrence of chemical reactions, ionization, and electric field effects. The overall aim of the program is to improve the performance of arcjet thrusters, which currently have an efficiency of about 35 percent.

The current design status of small rockets leaves much room for improvement, a situation our research is addressing with promising results. Performance gains in secondary propulsion, brought about by dependable simulation in the design process, will lead to lighter, less expensive satellites with longer lifetimes.



Iain D. Boyd is an assistant professor in the Sibley School of Mechanical and Aerospace Engineering. He is an expert in the application of particle simulation techniques to problems involving nonequilibrium gas dynamics, with applications that include aerodynamics and rocket propulsion of spacecraft, materials processing, and nuclear physics. He is also interested in efficient numerical implementation of these methods on modern supercomputers, including a new parallel algorithm for the IBM SP-1 at the Cornell National Supercomputer Facility. Born in Paisley, Great Britain, he was educated at the University of Southampton, where he received the B.Sc. degree in mathematics in 1985 and the Ph.D. in aeronautics and astronautics in 1989. He worked as a research scientist at NASA's Ames Research Center before coming to Cornell. He is an associate editor of the Journal of Spacecraft and Rockets *and a member of the American Physical Society and the American Institute of Aeronautics and Astronautics.*

"Performance gains in secondary propulsion . . . will lead to lighter, less expensive satellites with longer lifetimes."

ON BOARD FOR STUDIES OF WAKE VORTEX DYNAMICS

Undergraduates in a Research Environment

by Charles H. K. Williamson

"one of the best aspects of the Cornell research environment is the excellence of the students"

In a university research program, undergraduates can be a surprisingly powerful resource.

I began to discover this soon after I joined the mechanical and aerospace engineering faculty four years ago, and set out to establish three experimental fluids laboratories. I soon found that one of the best aspects of the Cornell research environment is the excellence of the students, both graduate and undergraduate. A critical part of building up the laboratories has been played by undergraduates, and they have made valuable contributions to the research program—in more than one case, a whole new focus of research has been triggered by results from a student project. In this article I will discuss the program from the point of view of the undergraduate participation.

The Two-Way Benefits of Undergraduates in Research

The main purpose of Cornell's undergraduate research program is to give students the opportunity to become involved in ongoing research, working alongside professors and graduate students. A number of fellowships are available to facilitate this aim. For example, undergraduates working in our school's fluids laboratories have received fellowships from the NASA Cornell Space Grant, which is administered by Professor Peter Gierasch of Space Sciences, or Engineering Alumni Fellowships, which were established by James Moore, a 1962 Cornell engineering alumnus, and are administered by Professor Gerald Rehkugler for the College of Engineering. Each of these sources provides fellowships for about twenty undergraduates a year.

This research experience is extremely rewarding for the students. Of the twenty-three who have worked in my fluids laboratories over the past three years, most have gone on to graduate schools, including CalTec, M.I.T., Stanford, and California at Berkeley. Two of these students were awarded prestigious National Science Foundation Graduate Fellowships for their Ph.D. studies.

What may not be so well recognized is how much undergraduates can contribute to the research programs. In my case, their involvement was essential for getting my research program "off the ground" rapidly, and continues to help it progress. A few examples will illustrate how this comes about.

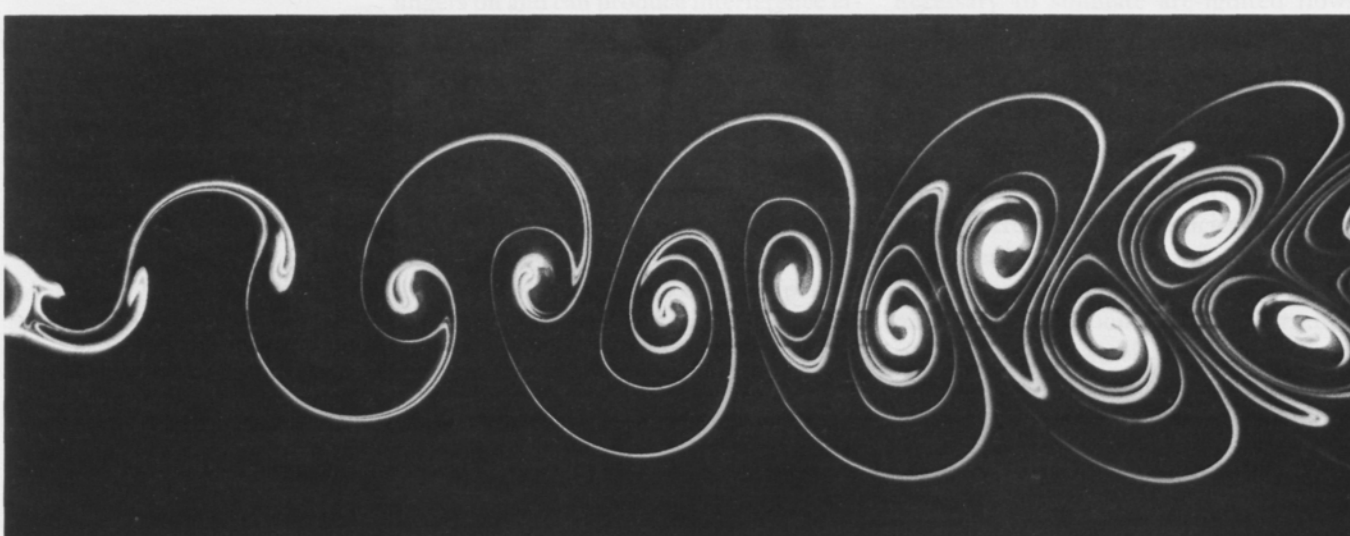
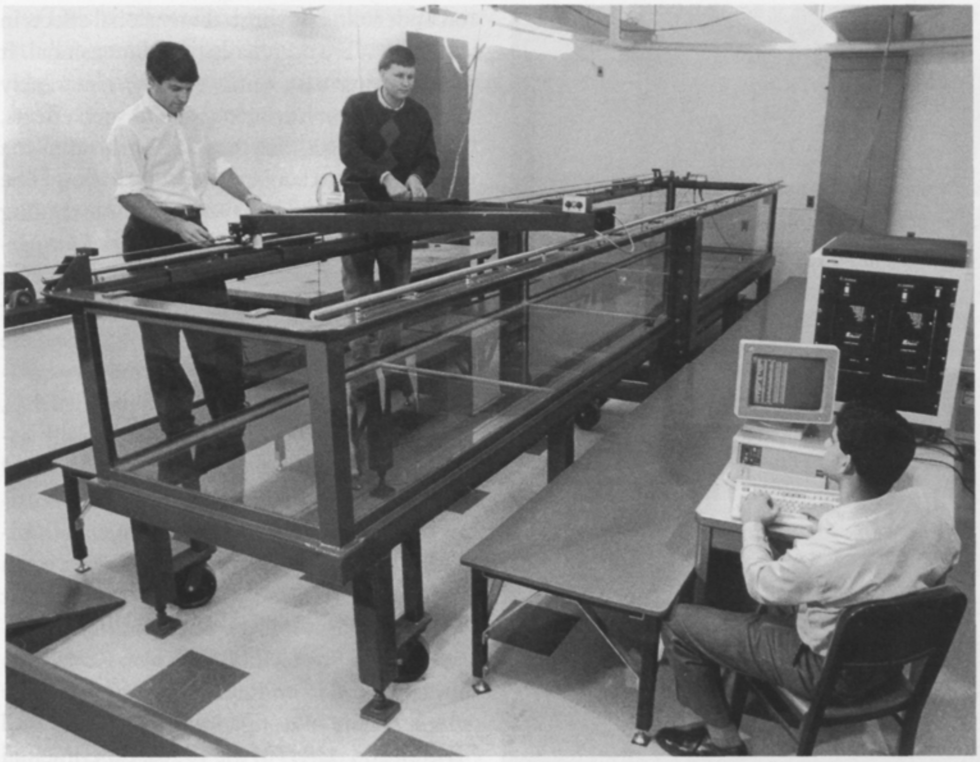


Figure 1. A classical regular pattern of wake vortices, known as a von Karman street. This photograph, taken in one of the Cornell fluids laboratories, shows a cross-sectional view of a sequence of alternating-sign vortices forming and shedding from a cylinder (at the left), and then moving downstream (to the right).



The Cornell computer-controlled X-Y towing tank. This novel facility, designed and constructed in 1990–91, comprises a 26-foot-long glass tank containing water through which we can propel bodies under "student-friendly" computer control in two degrees of freedom. It operates much like a giant X-Y computer plotter, but also allows joy-stick control.

Studies of Vortex Wakes Behind Nonstreamlined Bodies

One of the central research efforts of my group is concerned with the development of vortex wakes behind bluff (or nonstreamlined) bodies. Figure 1 shows a typical cross-sectional view of vortices that form behind a cylinder and are "shed" into the flow in the classic regular pattern known as a von Karman street.

Vortex wakes have technological significance. For example, their presence downstream of a body affects the pressure distribution on the body itself, sometimes causing vibrations that lead to fatigue and failure, or at least to a reduction in effectiveness of the structure. Typical areas in which wake studies are applicable include problems of wind force on structures such as buildings, chimney stacks, and bridges; wave and current loading on offshore structures; vibrations of riser tubes that pipe oil from the seabed to the surface; fluid loading of submarines and projectiles; and forces and moments on lifting surfaces at high angle of attack. The study of wakes and flow-induced vibration is of interest to the Office of Naval Research, the U.S. Air Force, and the National Science Foundation, as well as to industries involved in civil engineering, hydraulics, ocean engineering, and aerospace engineering. In addition to technological significance, the formation of wakes has fundamental scientific interest; in fact, it constitutes one class of shear flow (the others being mixing layers, jets, and boundary layers).

Our current research on wake vortex dynamics involves the use of wind-tunnel and water facilities. One of my first projects upon arriving at Cornell was to design a novel 26-foot-long computer-controlled X-Y towing tank that has since been built and is now housed on the ground floor of Upson Hall (see photo). The facility is capable of propelling bodies in two degrees of freedom through the water in the glass-sided tank, operating much like a giant X-Y plotter. Two undergraduates, Kurt Keller and Brad Short, aided by graduate student Greg Miller, were responsible for installing a "student-friendly" computer software system to control the two-way carriage system over the tank. We are able to "play" with the carriage motions through the use of an ingenious joy-stock control designed by student Elwood Miller.

The emphasis in the vortex-dynamics research, which stemmed from some initial work that I conducted at CalTec in the late 1980s, is

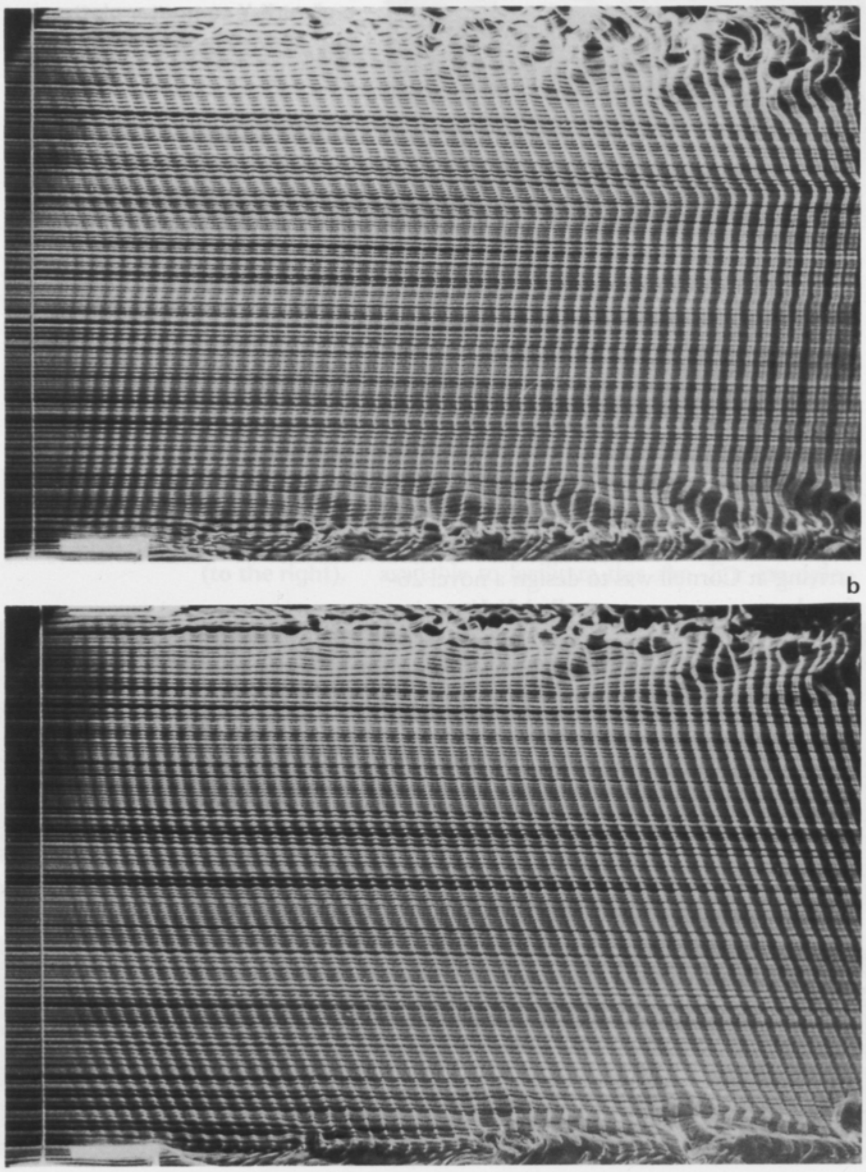
Figure 2. Transient oblique vortex-shedding patterns. The white lines mark the axes of the vortices in plan view; the vertical line at the left marks the cylinder.

The top photo shows a phase shock. A positive oblique vortex angle impulsively imposed by the boundary conditions at the top of the photograph moves downward into a region of smaller negative angle (in the bottom half). A rather different situation is shown in the bottom photo: a phase expansion is produced when a region of smaller positive vortex angle at the top is imposed on a region of larger positive angle.

The photographs were taken by research student Greg Miller, using smoke wire visualization in an ultra-low-turbulence wind tunnel.

a

b



on understanding three-dimensional effects in wakes that are nominally two-dimensional. It is surprising that, until recently, remarkably little attention has been given to such effects, despite the fact that they are intrinsic to the transition from laminar to turbulent flow. The research has shed light on some longstanding questions pertaining to these flows. Our particular approach is perhaps unusual in that it entails a strong element of discovery using simple experimental tools, in contrast to the tendency of researchers in most modern laboratories to become engrossed in the methods.

Until very recently, it was generally assumed that vortex-forming flows around nominally two-dimensional (cylindrical) bodies are predominantly two-dimensional. Actually, this is not normally the case, even in the "laminar regime" of vortex formation at low Reynolds numbers. Following the original work of Strouhal in 1878, von Karman in 1911–12, and Lord Rayleigh in 1915, and the more recent investigations of Roshko and Tritton and others in the 1950s, experimental work revealed surprisingly large discrepancies (around 20 percent) in relatively straightforward measurements of the normalized vortex-shedding frequency (the Strouhal number) versus the Reynolds number.

The origin of these discrepancies has been the subject of much debate in the literature for decades. In two of my own papers, in 1988 and 1989, I showed from measurements and simple visualizations that the vortices (when observed in plan view rather than in the orthodox cross-sectional view, as in Figure 1) can form at an oblique angle to the axis of the body itself, in what I have termed oblique shedding. This is shown in Figure 2. This oblique shedding of vortices is caused by the boundary conditions at the ends of a cylindrical body, even if the body is hundreds of diameters in length. Since the shedding angle influences the frequency, I was able to explain most of the scatter that had shown up in the literature. By manipulating the end conditions, I was further able to cause the occurrence of parallel shedding (in which the vortices are parallel to the cylinder axis), and so, for the first time, it became possible to make a valid comparison with the growing number of two-dimensional numerical simulations of this basic flow.

This work has led to a number of other studies, many of which are computational and analytical as well as experimental. We have developed a program involving close collaboration between our group at Cornell and groups in Europe—in Toulouse under Braza and Ha Minh, in Marseilles under Boyer and Provansal, in Lausanne under Peter Monkewitz, and in Nice under Pumir. In two of these collaborations—with Monkewitz and with the group in Marseilles—the approach is to model three-dimensional (phase dynamics) patterns using equations of the Guinzburg-Landau type. The emphasis is on the newly discovered transient phenomena, such as the "phase shocks" and "phase expansions" shown in Figure 2.

The Transition from Laminar to Turbulent Flow in Wakes

Another piece of research was actually triggered at Cornell by the work of undergraduate Kristen Gledhill, who worked with us in 1990–91 under the sponsorship of the NASA Space Grant and Engineering Alumni Fellowship programs.

While setting up a new smoke wire flow visualization technique in one of our wind tunnels, we observed (by chance, as it happens) a honeycomb-like three-dimensional pattern in the wake far downstream of a cylinder. This is shown in Figure 3a. Such was our excitement and curiosity on observing this phenomenon that it completely changed the focus of research for Ph.D. student Anil Prasad. In a two-year investigation we found that the phenomenon involves an interaction between oblique shedding waves from upstream and a set of two-dimensional waves that grow far downstream as a result of hydrodynamic instability. We further discovered a mechanism by which a nonlinear (quadratic) interaction of these two wave systems triggers the evolution of a third set of large-angle oblique waves (shown in Figure 3b). The discovery of this "oblique wave resonance," as we called it, was very exciting, since it was the first time it had been observed in a shear flow. The phenomenon has some relation to the now-classical work of Craik in the early 1970s on wave interaction in boundary-layer instability, but the oblique wave resonance we observed is markedly different from the several theoretical models that have been

a

b

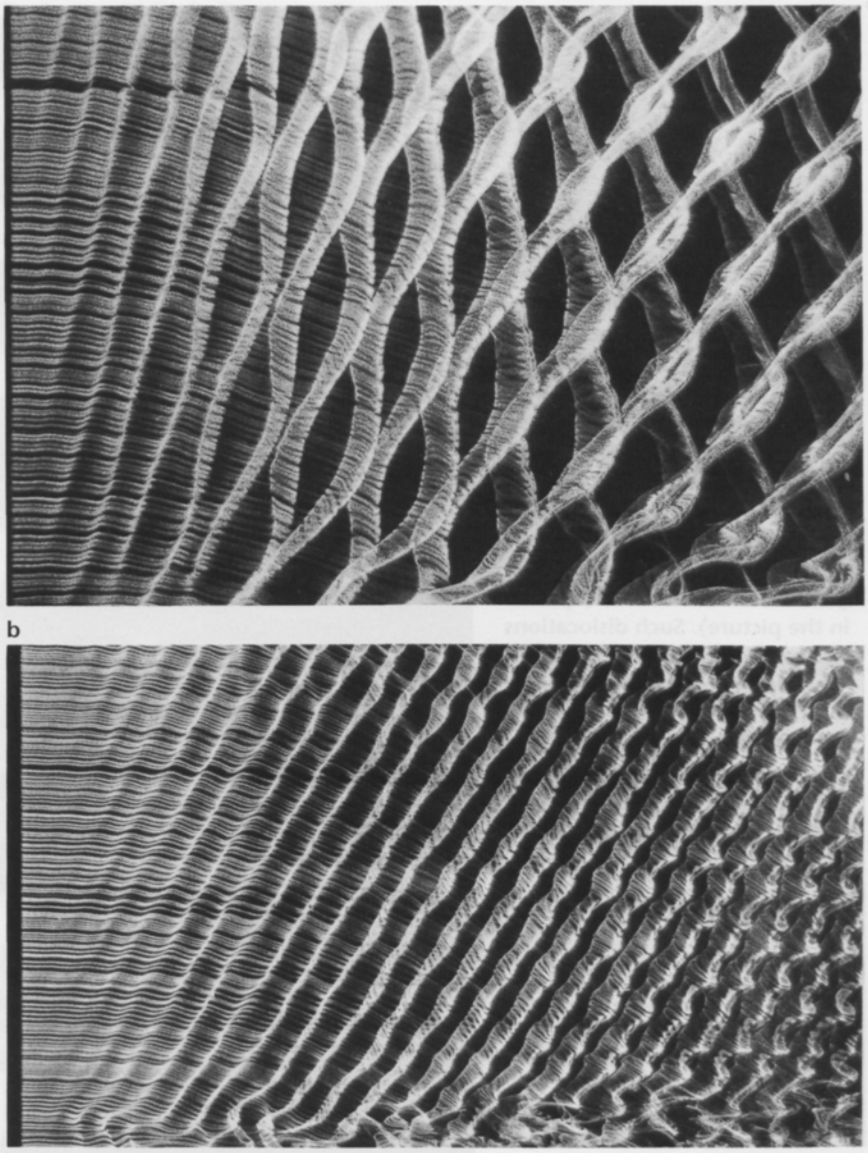
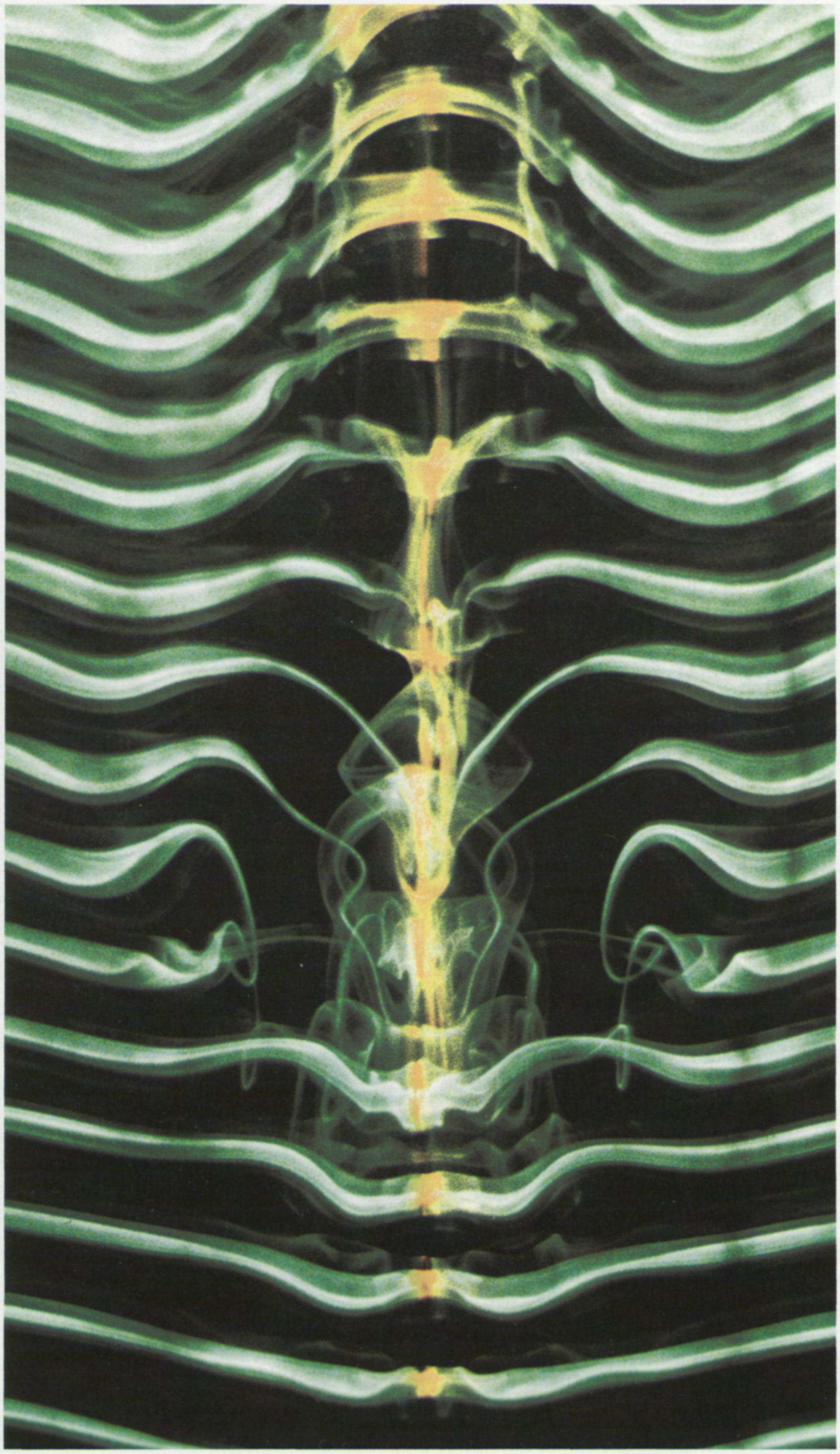


Figure 3. The discovery of a mechanism for "oblique wave resonance." The top photograph shows interaction between small-angle oblique waves at the left with two-dimensional (vertical) waves in the center, yielding large-angle oblique-resonance waves at the right. If the smoke wire is placed further downstream, as in the bottom photograph, then all that visually remains are the large-angle oblique-resonance waves. This is the first time that oblique-resonance waves of this form, coming from quadratic nonlinear interactions of two other waves, have been observed clearly in any shear flow, and their experimental discovery is markedly different from the theoretical models that have previously been proposed to represent the wake.

Figure 4. Vortex dislocations, discovered by the Cornell researchers to be a fundamental structure in the transition of wakes from laminar to turbulent flow. A local phase mismatch between the central yellow region and the green regions to either side causes a vortex dislocation. The green lines are vortices, which are transported by the flow downstream (upward in the picture). Such dislocations cause velocity fluctuations up to two orders of magnitude larger than the fluctuations in a flow without dislocations. Their existence now explains the low-frequency irregularities of wake velocity found originally in 1954.



proposed over the last decade to represent the far wake. Our research has led to two recent papers in the *Journal of Fluid Mechanics* and a number of international presentations. We are now working with Alain Pumir of the Institut Non Linéare, in Nice, to characterize our results theoretically.

A further investigation, which involved both Kristen Gledhill and another undergraduate, Cameron Dales, concerns other flow phenomena that occur during the transition from laminar to turbulent flow in wakes. Although some of our earlier work had demonstrated certain modes of small-scale three-dimensional instabilities acting on the primary "Karman" vortices, it was a surprise to discover that, in transition, the wake exhibits structures of relatively enormous scale. It has usually been assumed that when a two-dimensional shear flow undergoes transition, the primary instability waves or vortices extend continuously across the complete span of the flow. We discovered, on the contrary, that in a transitional wake the vortices form in cells, on the boundaries of which the vortices are mismatched so as to form phase dislocations (in broad analogy with some phenomena in materials science). A schematic of a localized phase dislocation in shown in Figure 4.

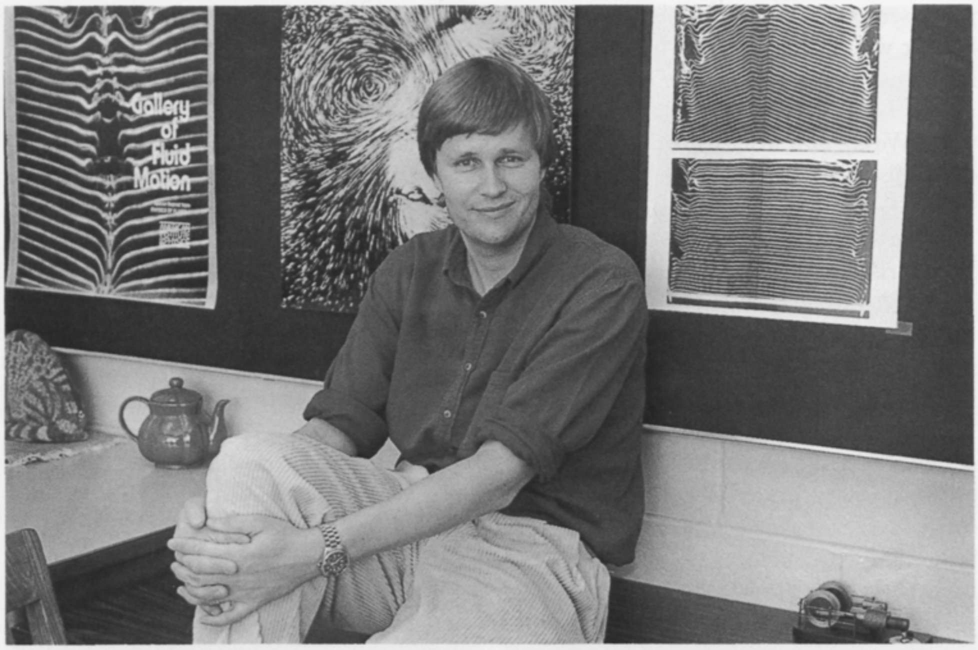
It is unclear why the existence of vortex dislocations has been unreported in the literature despite the fact that they can form large-scale turbulent structures up to fifteen times the size of the primary vortex wavelength. Dislocations are a central physical phenomenon in transitional wakes, significantly affecting a transfer of turbulent kinetic energy from small to large scales. Their presence explains the irregularities in wake velocity measurements that have remained unexplained since the classical work of Anatol Roshko in 1954. Furthermore, the fact that similar "defects" are now being observed in mixing-layer flows by Fred Browand's group at the University of Southern California and Patrick Huerre's group at École Polytechnique in Paris suggests that dislocations could well be an essential feature of turbulent transition in all shear flows. The observation and identification of vortex dislocations may turn out to be a significant discovery.

Reducing Vehicle Drag: An Innovation Pioneered by Undergraduates

Among all the many undergraduates who have participated in our research program, there are two whose story I would like to tell because their project appears to have some significance in engineering design. The story also illustrates the great enthusiasm undergraduates have for becoming involved in research.

In the fall of 1992 I introduced into our senior laboratory course (MAE 427) an experiment that involved a simple and passive means of reducing the drag on a bluff body (a cylinder) by interfering with its wake. The idea, adapted from Roshko's work in the 1950s, was to place a splitter plate parallel to the oncoming flow and downstream of the body, to disrupt the formation of wake vortices. In our experiment the procedure resulted in a modest drag reduction of about 20 percent. Following the class session, two undergraduates, Ashok Tripathi and Jonathan Miller, approached me with a view to extending the idea by placing plates at various orientations both upstream and downstream of the body. We have since found a number of interesting drag-reduction phenomena, including one that results from the shielding effect of placing plates upstream; the effect is similar to the reduced drag of one racing car when close behind another. We found that we could reduce the drag on the cylinder by 100 percent—to no drag at all—by situating a plate some distance upstream. What is especially surprising is that the width of the front plate need be only around one-third of the cylinder diameter to effect this result! Of practical importance is the fact that the drag of the whole system, comprising plate plus cylinder, is reduced to 40 percent of the drag of the cylinder without the plate.

The nature of this work led us to develop a new experiment for the senior laboratory course for the fall 1993 term. The 150 students were required to optimize the geometrical configuration so as to minimize system drag. A surprising aspect of this rather simple project is that it appears that such results have not yet been published or fully exploited. The students relish the idea of producing new, unpublished results as part of their course work. One can imagine *"working with undergraduates is not only a great pleasure, but highly beneficial to the projects."*



many applications: for example, to the design of vehicles on the road or in aerospace, where even a modest reduction of aerodynamic drag would have significance.

Developing the Program and the Research Team

Although the study of wake vortex dynamics has been our central research area, we are investigating other flows as well. Subjects we are looking into include the three-dimensional transition to turbulence in general shear flows, unsteady aerodynamics, automobile aerodynamics, problems in ocean engineering and naval architecture, the instabilities of trailing vortex pairs shed from aircraft wings, and vortex dynamics in general.

In our work so far, undergraduate students have been active participants, along with the graduate researchers, and this will continue. The arrangement is good for all of us. The undergraduates find the collaboration rewarding and exciting and it stimulates their hopes and plans for careers in research and development. The graduate students and I find that working with undergraduates is not only a great pleasure, but highly beneficial to the projects. Clearly, one of our best resources in the research environment is our undergraduates.

Charles H. K. Williamson is an associate professor in the School of Mechanical and Aerospace Engineering. He is interested in a variety of problems in fluid mechanics, often from an experimental perspective, and many students, at both the graduate and undergraduate levels, are involved in his research. Born in England, he received his undergraduate education at the University of Southampton (coincidentally sitting in the same chair later occupied by Iain Boyd). After receiving the doctorate from Cambridge University in 1982, Williamson worked as a staff engineer for a firm involved in research on offshore oil platforms and then as a high school mathematics and physics teacher in London. He took six months off to compete in yachting events, including two world championships. He came to the United States in 1984 and spent five years as a research fellow at the California Institute of Technology's Graduate Aeronautical Laboratories before joining the Cornell faculty in 1990. He was awarded the Calder Prize by the Royal Institution of Naval Architects in 1979 and three times won the Gallery of Fluid Motion competition at the annual meeting of the American Physical Society.

COMPUTATIONAL METHODS IN AERODYNAMIC DESIGN

The Difficulties and the Promise

by David A. Caughey

In a time when computers have become essential in engineering and science, aerodynamics presents a special case. Today's supercomputers, or even the most powerful computers we can imagine, cannot fully cope with problems involving fluid flow past vehicles, and the testing of physical models remains a useful tool. Yet the use of computational methods holds great promise in aderodynamics.

This promise was pointed out almost fifty years ago by John von Neumann, a remarkable pioneer in many fields spawned by the invention and development of the high-speed digital computer. A 1946 paper includes the passage:

> Indeed, to a great extent, experimentation in fluid mechanics is carried out under conditions where the underlying physical principles are not in doubt, where the quantities to be observed are completely determined by known equations. The purpose of the experiment is not to verify a proposed theory but to replace a computation from an unquestioned theory by direct measurements. Thus, wind tunnels are, for example, used at present, at least in part, as computing devices of the so-called analogy type. . . to integrate the non-linear partial differential equations of fluid dynamics.

The need to "replace a computation . . . by direct measurements" is still with us, despite the fact that aerodynamics is virtually unique among the engineering sciences in having a generally accepted and complete mathematical framework for describing problems of practical interest. The problem is that the solution of equations pertaining to the physics of fluid motions—at least under conditions corresponding to most engineering problems, and certainly for the flow of air past vehicles under all but the most rarefied conditions—requires calculations too massive for computers alone. Because of the fundamental difficulty of solving the governing equations, computational methods have been particularly important in the development of aerodynamics, and vice versa. In fact, aerodynamics—the study of fluid flow past vehicles—has been a forerunner in the development of computational methods. Today computational fluid dynamics (CFD) can be used in combination with wind-tunnel testing to improve the design process.

In this brief article, I shall try to give a picture of the difficulties and the promise of computational methods for the aerodynamic design of aircraft. I will focus on a concrete problem—the design of a wing for efficient flight at transonic speeds (where the speed of the aircraft is comparable to the speed of sound). This is a problem of great practical importance, since half the jetliners in the United States airline fleets are more than twenty years old and ready for replacement.

This modern jet-powered airliner is designed to operate efficiently at the lower end of the transonic speed regime—that is, when the flight speed is comparable to the speed of sound (approximately 340 meters per second or 760 miles per hour under standard sea-level conditions in the atmosphere). The speed of this McDonnell-Douglas DC-10, and all similar subsonic transport aircraft, is limited by the incremental drag associated with the formation of shock waves above the wing surface.

The Fundamental Difficulties in Solving Aerodynamic Problems

The physics of fluid motions are well described, under most conditions, by the set of

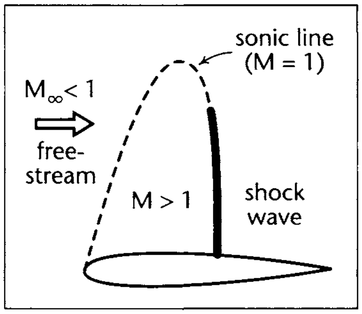


Figure 1. A schematic representation of the flow pattern in the vicinity of a lifting wing section when the flight Mach number is sufficiently high that a supersonic pocket, terminated by a shock wave, forms in the vicinity of the wing upper surface.

partial differential equations known as the Navier-Stokes equations. The difficulties associated with solving aerodynamic problems arise from two (related) properties of these equations:

1. *Nonlinearity.* As a result of the nonlinearity of the Navier-Stokes equations, most techniques of classical mathematical analysis are not generally applicable; in particular, it is not possible to use superposition of elementary solutions to build up more complex solutions. In addition, the nonlinearity can lead to the formation of nearly discontinuous jumps, or shock waves, in flows that are initially smooth.
2. *The tendency for turbulence to develop.* The existence of turbulence in most flows of engineering interest means that to compute even the mean properties of these flows, it is necessary to determine unsteady solutions to the Navier-Stokes equations which resolve all the physically important fluctuations due to the turbulence. When computational methods are used to compute turbulent flows directly from the unsteady Navier-Stokes equations, the requirement to resolve all these scales for practical problems results in an impractically massive calculation. For problems of practical interest, therefore, phenomenological models are usually relied on for predicting the effects of turbulent fluctuations on the mean flow fields.

It is, of course, more than a coincidence that von Neumann identified the study of turbulent flows and flows containing shock waves as two important problems for which numerical methods would play a crucial role.

The Combination of Computers and Wind Tunnels

The time-honored method of aerodynamic testing is, of course, to build models and observe their behavior in a wind tunnel; such testing provides measurements of aerodynamic forces and rates of heat transfer. But development of the techniques of computational fluid dynamics has led to debate, lively at times, about the prospect of the computer replacing the wind tunnel as the primary tool for evaluating aerodynamic designs.

Computational analyses of flight vehicle designs typically can be done much more quickly than wind-tunnel testing; minor geometric modifications to design can be analyzed without the expense or time required to build physical models, and the use of a computer is much less energy-intensive than wind-tunnel testing. On the other hand, in computational analyses it is almost always necessary to make approximations—including simplifications of the fluid-mechanical model and, often, of the geometry—and the net effects of these approximations are usually difficult to assess.

Wind-tunnel testing has the advantage that with proper scaling it is, in principle, a perfect simulation of the relevant physical processes. The proper scaling is almost never achieved completely in practice, however, because of the presence of the walls of the wind tunnel and because of the difficulty in simultaneously adjusting the parameters that govern all the relevant physical processes.

In view of the limitations inherent in each of these technologies, it is likely that for the foreseeable future, aerodynamic designers will continue to rely on both the computer and the wind tunnel. Increasingly, however, computational analyses are used to screen many more candidate configurations than could possibly be tested in the wind tunnel during the design process. As a result, much better designs can be achieved with the same amount of wind-tunnel time.

Transonic Flow and the Problem of Shock Waves

For many design purposes, it is sufficient to represent the flow past the vehicle as that of an ideal (or inviscid) fluid. This is appropriate when the dimensionless parameter known as the Reynolds number, which can be interpreted as an inverse ratio of the relative importance of viscous, or frictional, effects in determining the properties of the flow, is sufficiently large and the body is sufficiently streamlined that there are no large regions of separated, or reverse, flow. For most aircraft, these conditions are satisfied under flight conditions corresponding to the design, or cruise, speed and altitude.

When frictional effects have been neglected, the Navier-Stokes equations simplify to the Euler equations of inviscid flow. Then for aerodynamic problems, the Mach number M is the only remaining dimensionless parameter of significance. The flight Mach number represents the ratio of the vehicle flight speed to the speed of sound in the undisturbed atmosphere. Since the propagation of pressure signals causes information about the flow to be communicated from one point to another in the field, it is not surprising that the character of the Euler equations changes dramatically depending upon the local Mach number —whether $M < 1$,in subsonic flow, or $M > 1$, in supersonic flow.

Figure 1 presents a schematic representation of the flow field in the vicinity of an airfoil, or wing section, for flight Mach numbers characteristic of the cruise condition for a jet transport aircraft ($0.70 < M < 0.90$). A pocket of locally supersonic flow develops above the wing as a result of the acceleration of air flow that is required to generate the low pressures needed for lift. This pocket of supersonic flow is almost always terminated by a shock wave—a very high-gradient region in which the fluid velocity changes abruptly from supersonic to subsonic, with an attendant increase in the density and pressure of the fluid. It is the additional drag associated with the formation of these shock waves that limits the speed at which airliners can fly economically.

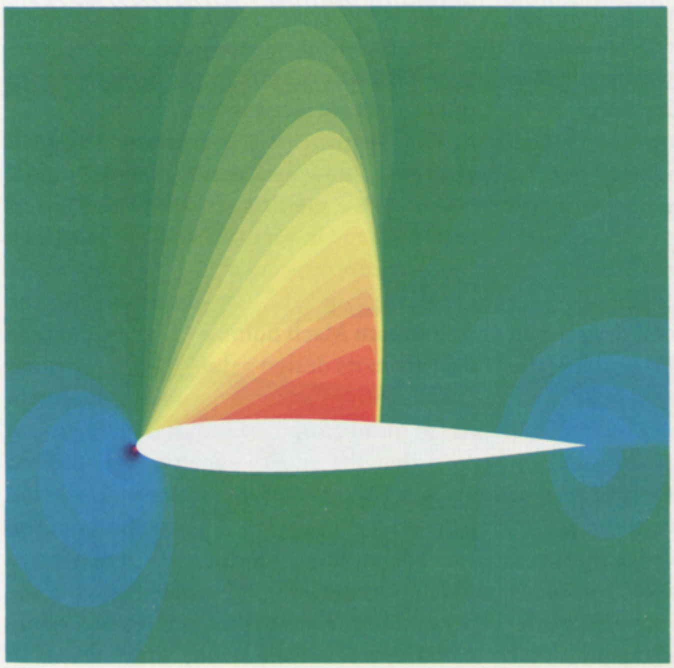
Figure 2 presents results of a computation in which the Euler equations are solved for the flow past a profile of classical design (the NACA 0012 airfoil) at a free-stream Mach number of $M = 0.75$ and at an angle of incidence of 2.92 degrees. The different contours (colors) in this plot represent various Mach numbers, with $M = 1$ corresponding approximately to the boundary between green and yellow. In such a contour plot the Mach number is analogous to elevation in a topographic contour map; thus, a bunching of the contours indicates a steep gradient in the Mach number. The rapid change in color from red/orange to green along the line springing from the upper surface of the airfoil indicates a rather strong shock wave across which the local Mach number changes from more than 1.4 to less than 0.7.

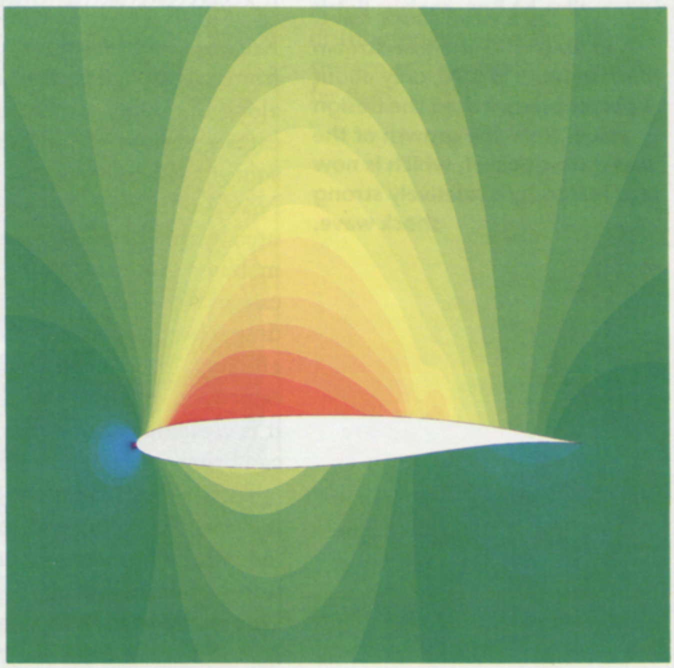
Until the late 1960s, many aerodynamicists thought it was impossible to avoid the formation of these shock waves in flight at transonic Mach numbers. A number of arguments were put forth purporting to show that the supersonic flow in a smoothly decelerating region near the surface of a wing is inherently unstable and would always be terminated by a shock wave. By the early 1970s, however, both numerical computations and physical experiments had convinced engineers that so-called shock-free flows did, in fact, exist. Numerical techniques were developed both to predict the shapes for which such shock-free flows could be achieved and to analyze the resulting flows at design and off-design Mach numbers.

Figure 3 shows a color contour map of

Figure 2 (left). Contours of constant Mach number for the computed flow pattern in the vicinity of the NACA 0012 airfoil section. The diagram shows results of numerical solution of the Euler equations of inviscid compressible fluid flow at a free-stream Mach number of 0.75 and 2.92 degrees angle of incidence. Note the rapid change of color associated with the shock wave extending from the upper surface of the airfoil.

Figure 3 (right). Contours of constant Mach number for the computed flow pattern in the vicinity of the Korn airfoil section. In this case, the contours present the numerical solution of the Euler equations at the shock-free design point corresponding to a free-stream Mach number of 0.75 and an angle of incidence of 0 degrees. Note the gradual transition of color associated with the smooth recompression of the flow from supersonic to subsonic velocities along the upper surface of the airfoil.





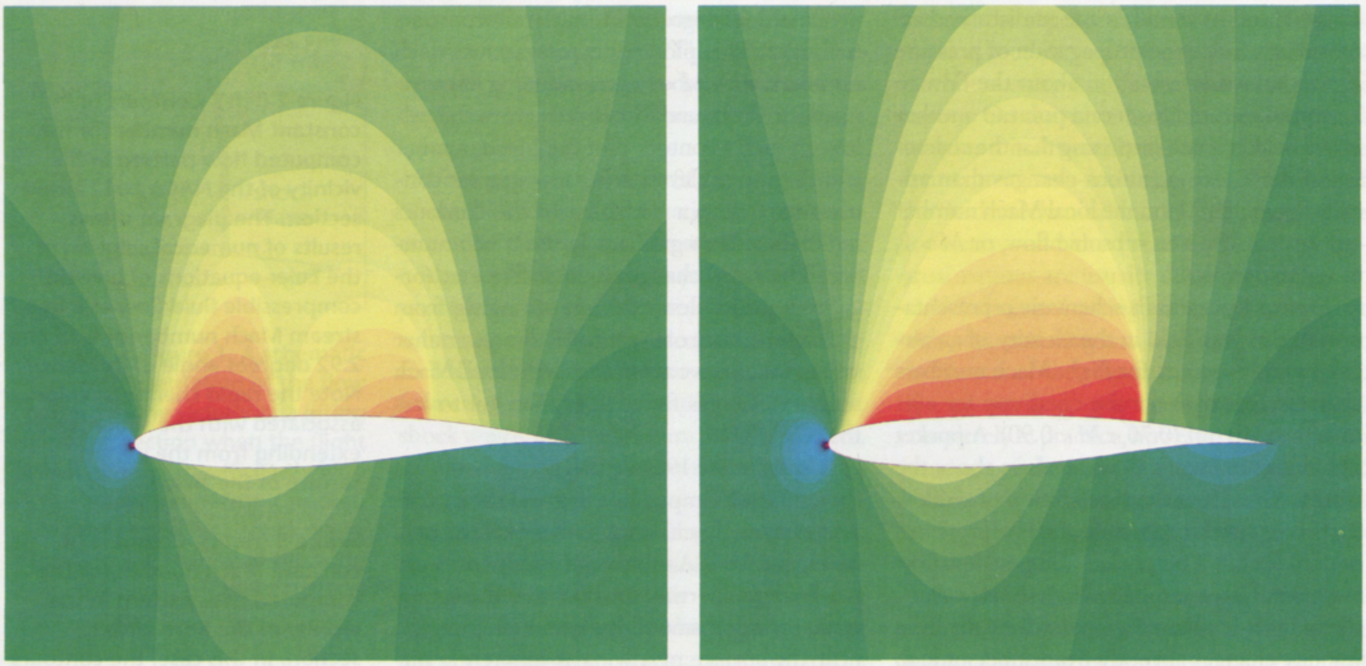


Figure 4. Contours of constant Mach number for the computed flow pattern in the vicinity of the Korn airfoil section at slightly off-design Mach numbers. In 4a (left) the free-stream Mach number is 0.74, only about 1 percent lower than the design value. Note the breakup of the supersonic pocket into two smaller pockets, each terminated by a weak shock wave. In 4b (right) the free-stream Mach number is 0.76, only about 1 percent larger than the design value. Note the growth of the supersonic pocket, which is now terminated by a relatively strong shock wave.

the computed Mach number distribution in the vicinity of a shock-free airfoil designed by David Korn at New York University. These results were computed using the same inviscid approximation that was used to calculate the results for the NACA 0012 airfoil shown in Figure 2. In spite of the fact that the same free-stream Mach number was used in both sets of calculations, and that almost exactly the same lift is generated, no significant shock wave is indicated for the Korn airfoil: the smooth variation in color from red through orange and yellow to green along the upper surface of the airfoil indicates a smooth recompression from supersonic to subsonic velocity. In the case of the NACA 0012 airfoil, the wave drag contributed by the shock wave amounts to approximately 5 per cent of the lift force; in the case of the shock-free Korn airfoil, this wave drag is zero. And since the total drag for an efficient high-speed transport is typically only about 5 per cent of the lift generated, it is clear that shock-free wing technology can bring about appreciable savings in fuel.

While this comparison demonstrates that it is possible to design airfoils and wings having zones of supersonic flow with no shock waves, the fact remains that such flow fields are quite special. In fact, an important mathematical result from the 1960s implies that for a flow with a smooth supersonic recompression, any infinitesimal perturbation in the free-stream conditions or in the shape of the airfoil will result in the formation of a shock wave. This finding was misinterpreted by many to imply that shock-free flow fields are not achievable in practice because arbitarily small perturbations would result in catastrophic breakdown of the flow field. In actual fact, even though the flow fields are relatively sensitive to perturbations away from the design point, a small perturbation usually results in the appearance of only relatively weak shocks.

To illustrate this sensitivity to small changes in flow parameters, two additional solutions for the flow past the Korn airfoil are presented in Figure 4. Calculated Mach number contours are shown for the flow at the design angle of incidence, but with the free stream Mach number perturbed by +/– 0.01 from its design value. Figure 4a shows the Mach number contours for a free-stream Mach number of 0.74 rather than 0.75; it is seen that the supersonic zone has broken up into two smaller lobes, each terminated by a weak shock wave. Figure 4b shows the Mach number contours for a free-stream Mach number of 0.76; in this case, the supersonic zone has grown and is now terminated by a relatively strong shock wave.

The Numerical Method and Its Significance

The results shown in the figures were obtained by using the relatively new tool of computational fluid mechanics, and serve to demonstrate its usefulness in improving the design of commercially important aircraft.

The procedure used in these calculations is one that I developed on the basis of a finite-volume approximation to the differential equations. The domain is divided into a non-overlapping set of mesh cells and the appropriate conservation laws are enforced for each cell to determine the average values of the flow variables there. The grid system used for the Korn airfoil calculations is illustrated in Figure 5. Although the actual grid system extends to approximately thirty body lengths from the airfoil, only the grid cells near the airfoil surface are shown here for clarity; the entire grid contains more than 24,000 cells.

The finite-volume approximation is designed to capture, automatically, with the correct strengths and locations, any shock waves that appear in the solution. The numerical method enforces conservation of mass and energy and Newton's second law relating acceleration to the net pressure force acting on the fluid in each of the quadrilateral cells into which the domain has been subdivided. Since there are four equations to be solved to relate the fluxes across the boundaries of each cell to the average properties within the cell and within neighboring cells, for this example almost 100,000 simultaneous equations are required in order to determine the flow properties throughout the field. These nonlinear equations are solved using an efficient iterative technique that, in most cases, converges to within acceptable accuracy in fewer than fifty iterations.

The aerodynamic phenomenon discussed here—the generation of shock waves above the

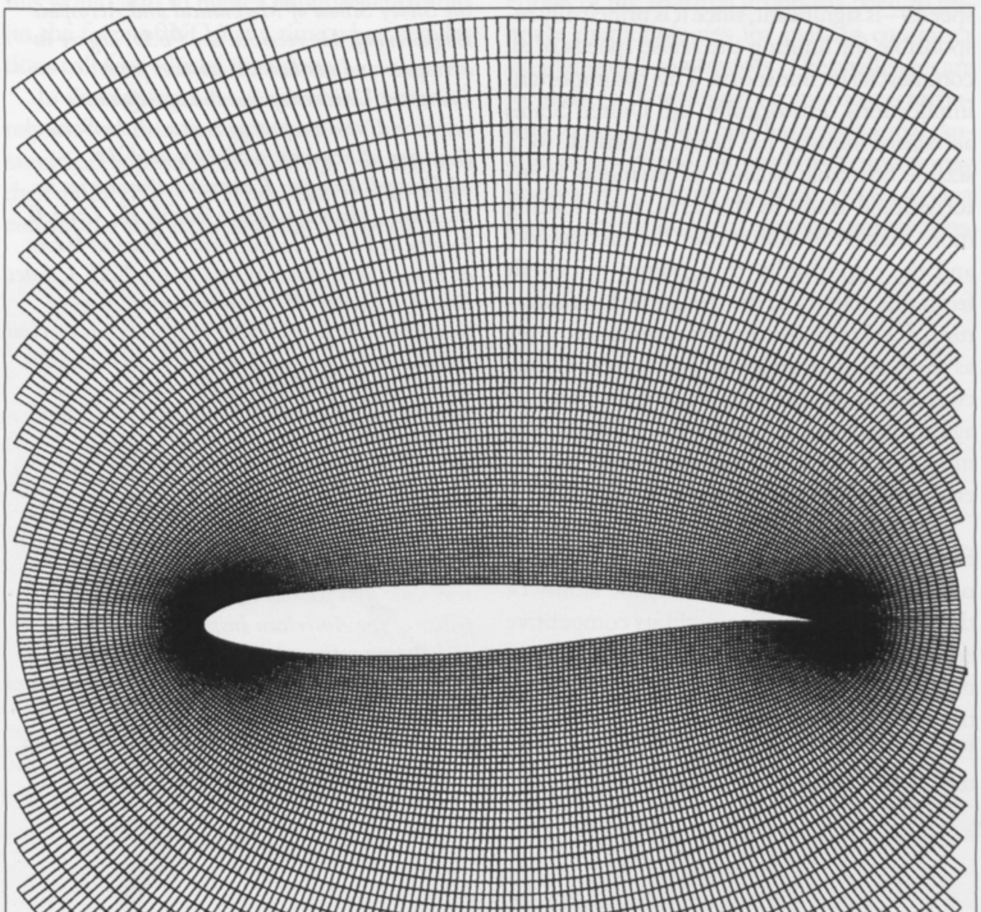
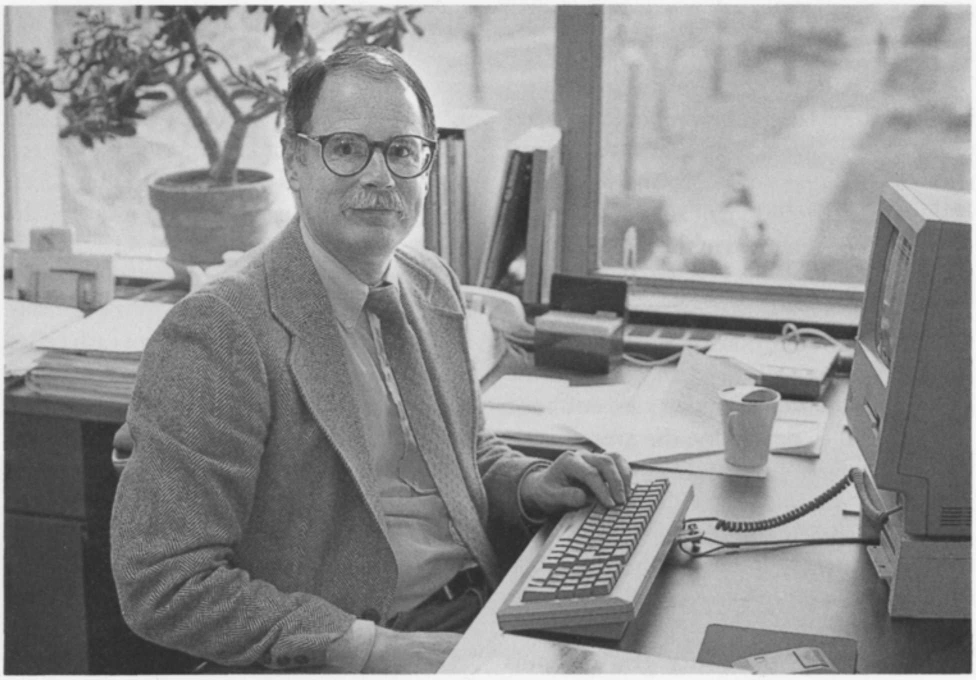


Figure 5. Part of the grid system devised for the calculations used to predict the Mach number distribution shown in Figures 3 and 4. The portion shown here is near the surface of the Korn airfoil. The entire grid contains 384 cells in the direction of the contours that wrap around the airfoil surface, and 64 cells distributed between the airfoil surface and the boundary in the far field.



"the replacement of . . . aging transports with more fuel-efficient new models will have a beneficial impact on the environment."

wing of an aircraft cruising at transonic speeds—is significant, since it is principally responsible for limiting the cruise speeds of all commercial jet transports. This has important implications. Historically, the United States aerospace industry has been responsible for a sizable favorable balance of payments in international trade in this area, contributing more than $150 billion over the past decade, and the opportunity to continue to benefit from this activity in the design and manufacture of civil transport aircraft continues to grow as the world's commercial jet transport fleets continue to age. Also, the replacement of these aging transports with more fuel-efficient new models will have a beneficial impact on the environment.

At a time when the aerospace industry is facing dramatic challenges due to a restructuring of the defense industry, the ability of the United States to maintain its competitive edge in this important technology will be a major factor in helping the aerospace industry weather the changes in the coming years. Better design, involving new computational techniques, is a key to success.

David A. Caughey is a professor and director of the Sibley School of Mechanical and Aerospace Engineering. He received the Ph.D. degree in aerospace and mechanical sciences from Princeton University and did aerodynamic research at the computing center of the Soviet Academy of Sciences in Moscow and the McDonnell Douglas Research Laboratories in St. Louis, Missouri, before joining the Cornell faculty in 1974. He has spent sabbatical leaves at Princeton University and at the NASA Ames Research Center. His research interests have focused on the development of efficient numerical techniques for problems in compressible aerodynamics, with particular attention to transonic flows with shock waves. He received the 1979 Lawrence Sperry Award of the American Institute of Aerodynamics and Astronautics and a certificate of merit from the NASA Langley Research Center for his contributions to a widely-used computer code for the analysis of transonic flow past wings. He is an associate fellow of the American Institute of Aeronautics and Astronautics, and has served as an associate editor of the AIAA Journal. *In 1977 he received the Cornell Society of Engineers/Tau Beta Pi Award for Excellence in Engineering Teaching.*

SIMULATING THE PERFORMANCE OF GAS-TURBINE COMBUSTORS

by Stephen B. Pope

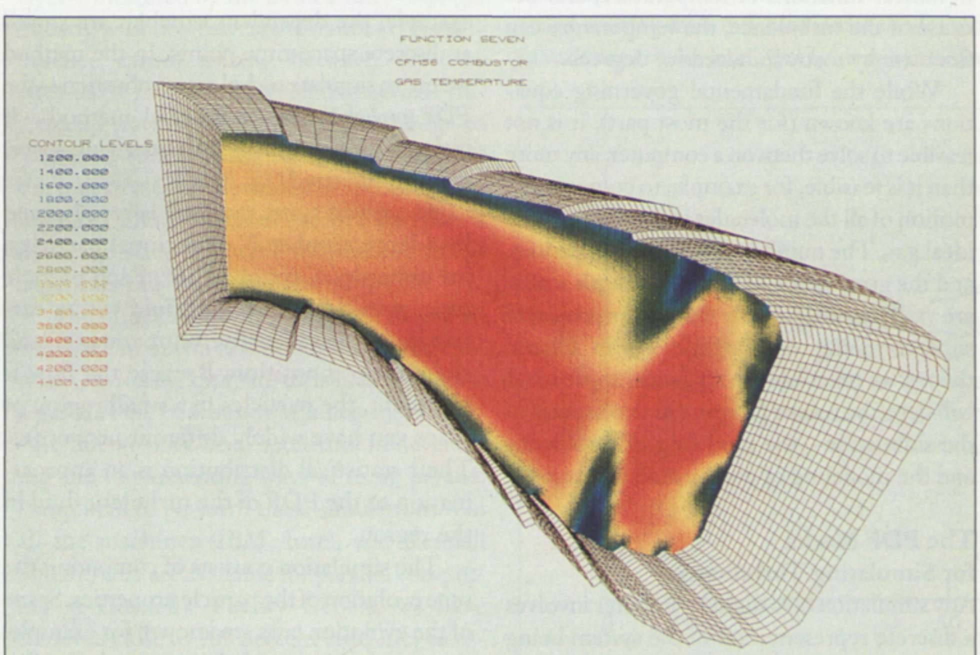
The combustors in gas-turbine engines must meet increasingly stringent requirements, and better methods for making design modifications are essential. The challenge is significant, for the manufacture of aircraft engines remains an important segment of the economy, with annual sales in the tens of billions of dollars.

While gas-turbine technology has existed for fifty years, it has had to adapt to continual changes in other technologies. Now, for example, advances in materials technology allow higher turbine inlet temperatures and therefore higher temperatures in the combustor. Without combustor design modifications, this would lead to higher pollution emissions (in the form of NO_x) at a time when regulations call for reduced emissions.

In developing new combustors, designers rely on two principal approaches. One is the empirical approach of building, testing, and then modifying prototypes. This is both time-consuming and expensive: the cost of running a test rig is on the order of $100,000 per day. The other strategy is to use computer simulations to predict performance. Simulation is extremely attractive because it is faster and much less expensive to implement. Furthermore, sales are increasingly based on the projected performance of engines that have yet to be developed, and computer simulations are used to make these projections. However, because the simulations now available are not completely accurate and because they do not predict all phenomena (for example, combustion instabilities), it is at present necessary to use both approaches in combustor design.

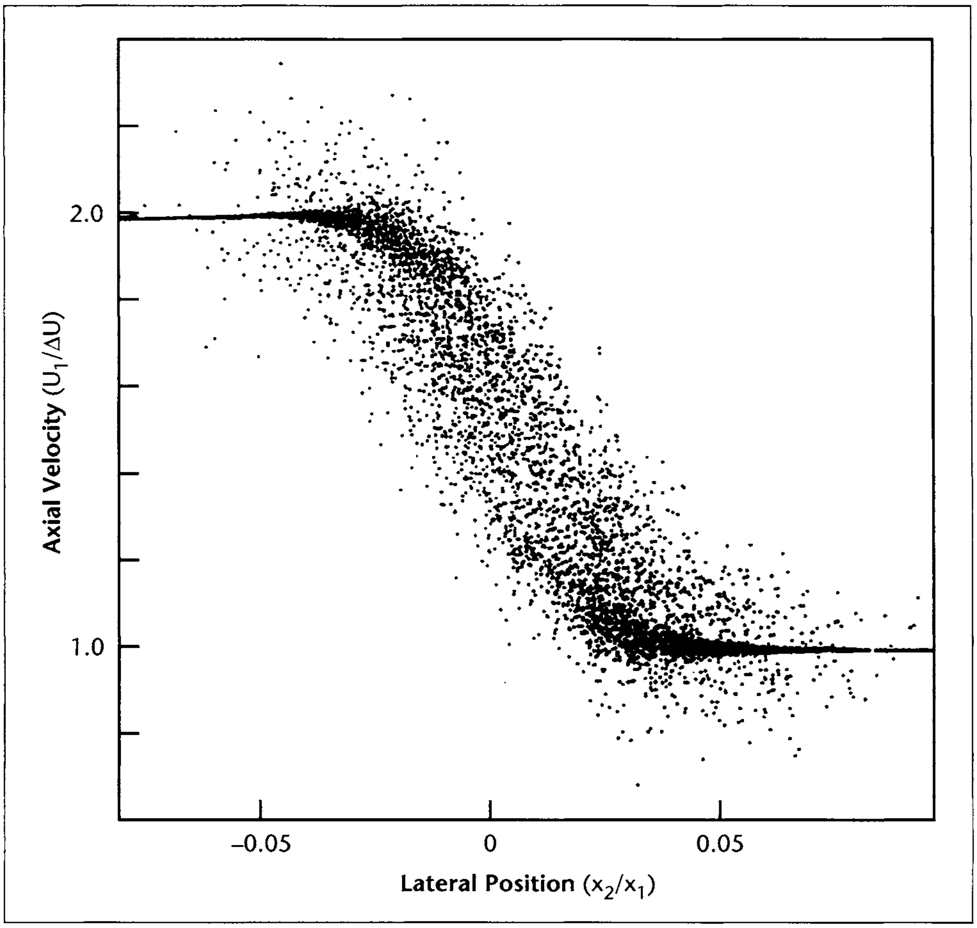
Over the past ten years, one of the main efforts of my research group has been to improve methodologies for making computer simulations of combustors. The challenges are formidable. The flow in a combustor is turbulent, so that the flow field has a substantial random component. Combustion chemistry may involve fifty or more chemical species, taking part in several hundred elementary reactions.

"Simulation is extremely attractive because it is faster and much less expensive"



Color contour plot of isotherms in a gas turbine combustor produced using General Electric's combustor simulation program.

Figure 1. Scatter plot showing results of a simple simulation, using the PDF model, of the distribution of particle velocities in a turbulent flow at a fixed time. The particles are located at a fixed distance, x_1, along the principal direction of flow, but are distributed at various positions, x_2, across the thickness of a constant-density plane mixing layer between two parallel uniform streams flowing at different velocities.



In addition, the reaction rates are highly nonlinear functions of temperature, and because of the turbulence, the temperature can fluctuate by many hundreds of degrees.

While the fundamental governing equations are known (for the most part), it is not feasible to solve them on a computer, any more than it is feasible, for example, to compute the motion of all the molecules in a milliliter of an ideal gas. The number of degrees of freedom, and the great range of time and length scales, are vastly more than any current or projected supercomputer can handle. As in kinetic theory, we must adopt a statistical approach. I will describe recent progress in two aspects of the simulation—the modeling of turbulence and the modeling of combustion chemistry.

The PDF Model for Simulating Turbulence

Any simulation on a digital computer involves a discrete representation of the system being studied. In many engineering applications it is the physical space and time that are discretized; in a finite-difference method, for example, the dependent variables are stored at discrete space-time points. In the method we use to simulate turbulent combustion—the *PDF (probability density function)* method— it is the fluid, rather than the underlying space, that is discretized.

At a given time, the flow is represented by a large number N of notional particles; for example, N could be 10^6. Each particle represents a fixed mass of fluid with a certain position, velocity, temperature, and chemical composition. Because the flow is turbulent, the particles in a small region of space can have widely different properties. Their statistical distribution is an approximation to the PDF of the turbulent fluid in the region.

The simulation consists of computing the time evolution of the particle properties. Some of the evolution laws are known; for example, the particles move with their own velocity. But models are required to simulate the effect of turbulent fluctuations on the particles' velocities and thermochemical composition.

Figures 1 and 2 show results from a simple simulation that illustrates the PDF method. The flow under consideration is the constant-density, nonreacting plane mixing layer formed between two parallel uniform streams of different velocity (in this example, one velocity is taken to be twice the other). The dominant flow direction is x_1 and the cross-flow direction (going from one of the parallel streams to the other) is x_2. (The flow is statistically homogeneous in x_3.) The free-stream velocities are U_∞ (at $x_2 = \infty$) and $2U_\infty$ (at $x_2 = -\infty$), so the velocity ratio is 2, and the velocity difference is $\Delta U = U_\infty$. At large axial distances the flow spreads linearly and is self-similar. Consequently, statistics of $U/\Delta U$ (velocity within the layer) depend only on x_2/x_1 (lateral position).

Figure 1 is a scatter plot of the particles' axial velocity U_1 and lateral position x_2 at a fixed axial location x_1 and fixed time. In the free streams ($x_2 \rightarrow \pm\infty$) the particles adopt the free-stream velocities ($2U$ and U, respectively). But in between there is a distribution of particle velocities that accurately represents the distribution of turbulent velocities.

Figure 2 shows the paths of five particles (selected at random from the N = 50,000 used in the simulation). The nominal edges of the layer—indicated by the dashed lines—spread linearly with downstream distance (x_1) as turbulence causes mixing between the two streams. It may be observed that several trajectories traverse the layer from one edge to the other, without changing direction, and that the trajectories are devoid of small-scale fluctuations. Thus, the model accurately reflects the large-scale coherent motions observed experimentally in mixing layers.

The simple simulation that I have described was done in only a few minutes at a workstation. Obviously, applying the same method to a gas-turbine combustor is much more difficult, but we have been successful in developing and implementing ways of using parallel computers to perform these simulations. On all the machines (IBM, Intel, and Kendall Square) that are available for parallel computing at Cornell's Theory Center, we have achieved close to 100 percent efficiency in using the capability.

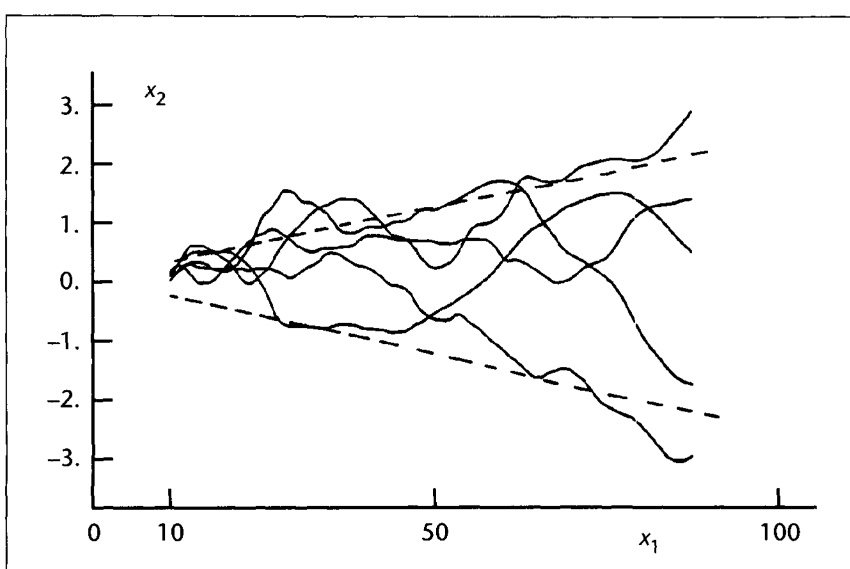
Simplifying the Description of Combustion Chemistry

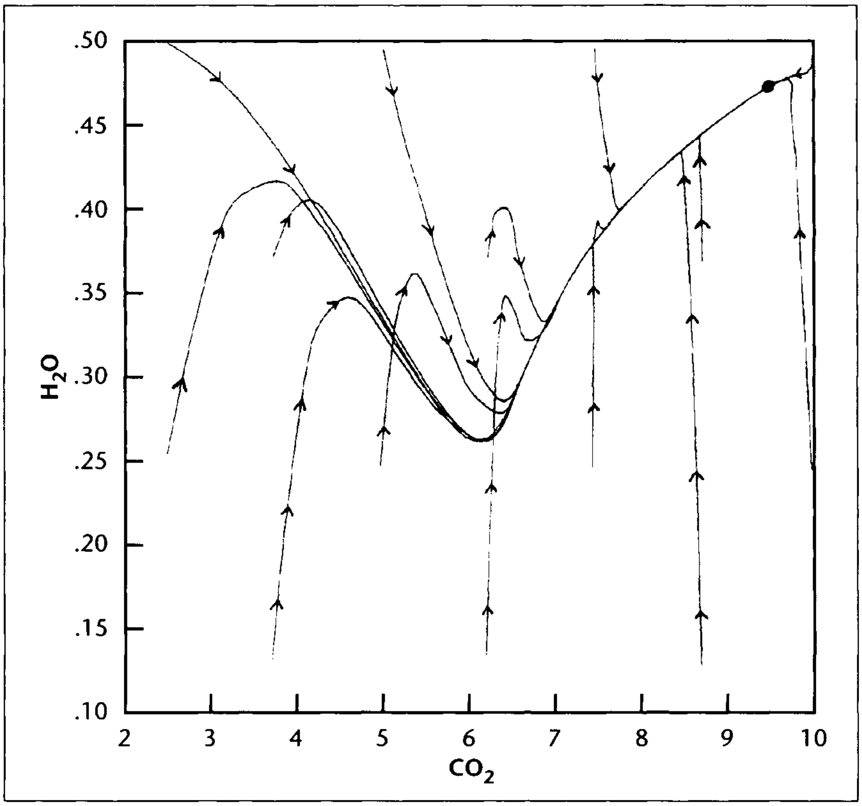
With fifty or so chemical species participating in several hundred elementary reactions, and with time scales ranging from 10^{-12} to 10^{-2} second, combustion chemistry is complex. In simple situations—in laminar flames, for example—it is possible to describe this chemistry in full detail, but for turbulent-flow simulations, a much simplified description is needed in order to make the computations tractable.

Together with Dr. Ulrich Maas of the University of Stuttgart, we have developed a methodology to simplify the representation of the chemical kinetics. We call it the *ILDM (intrinsic low-dimensional manifolds)* method. To understand the basic idea of ILDM, we can consider a reacting flow involving fifty species. The composition of a fluid particle in the flow can be represented (at a fixed time) as a point in a 50-dimensional composition space; then, as time goes on, the point moves in the space under the actions of chemical reaction and molecular diffusion. The ILDM method simplifies the situation by considering that instead of filling the 50-dimensional composition space, the particles are attracted to low-dimensional manifolds within the space.

The idea behind the ILDM method is illustrated in Figure 3, which shows the trajectories, starting from different initial conditions, of various particles in a CO/H_2/air system. The

Figure 2. The paths of five randomly selected particles from the Figure 1 simlulation. The distances x_1 and x_2 have arbitrary units. The dashed lines show the nominal edges of the mixing layer, taken to be where the mean velocity differs from the free-stream velocity by 10 percent of the velocity difference.





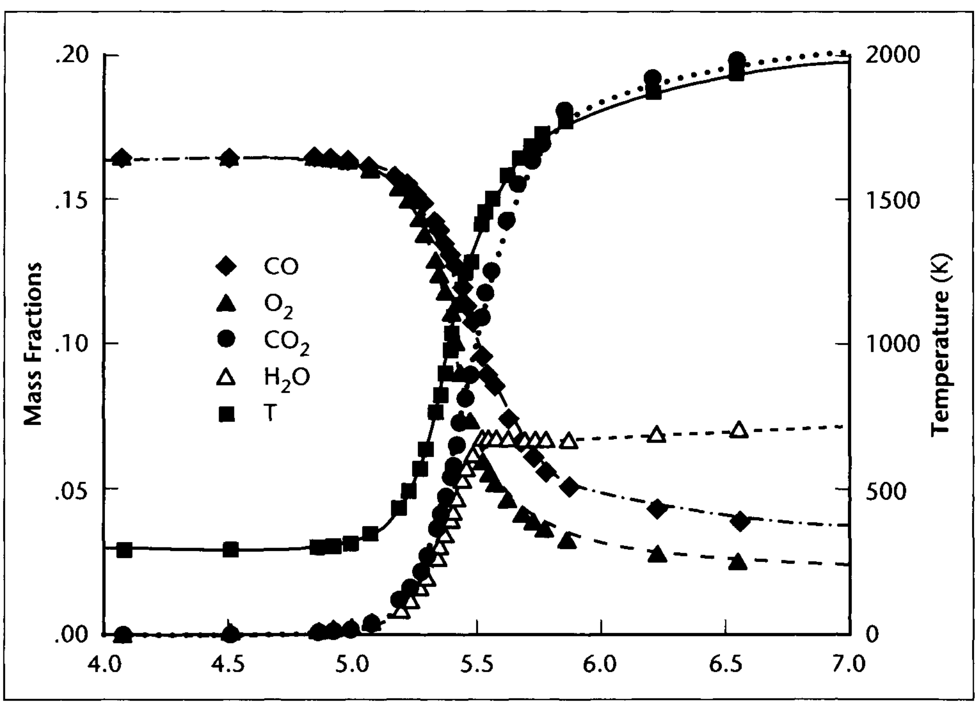
trajectories are projected onto the two-dimensional CO_2–H_2O plane. By construction, the initial conditions are distributed throughout the space; nevertheless, very rapidly the trajectories bunch together around a single curve: a one-dimensional manifold.

The ILDM method provides a mathematical prescription for identifying the intrinsic manifolds of specified dimensionality for any fuel/air mixture. The treatment of the chemistry is then greatly simplified by describing it on (for example) a two-dimensional manifold rather than in a 50-dimensional space. The greater the dimensionality employed, the better the approximation; but in applications studied so far, a two-dimensional manifold has been sufficient.

The accuracy of the method is demonstrated in Figure 4, which shows close agreement between results obtained with ILDM and with a more detailed representation. The figure shows calculated mass fraction profiles for several chemical species in a laminar premixed flame of a CO/H_2/air mix-

Figure 3. An illustration of the basic idea of the ILDM method for simulating combustion chemistry in turbulent fluid flows. Here the reaction trajectories of a number of particles of a CO/H_2/air combustion system are projected onto the $CO_2 - H_2O$ plane. Although the particles started from different initial conditions, they are all attracted to a single curve—in this example, a one-dimensional manifold. This "grouping" strategy greatly simplifies the calculations.

Figure 4. Data demonstrating the accuracy of ILDM simulation. The system is a premixed CO/H_2/air flame; temperature and mass-fraction profiles of the major chemical species are shown. The profiles were calculated using ILDM simulation (the symbols) and using a detailed kinetic scheme (the lines).



ture. The solid lines were obtained using a scheme involving thirteen species and sixty-seven reactions; the symbols indicate results obtained using the ILDM method with a two-dimensional manifold.

The Use of Models in Turbulent Flame Calculations

We have used the PDF turbulence model in combination with the ILDM chemistry model to make calculations of velocity, density, and composition in turbulent flames. Comparison of such calculations with careful laboratory measurements serves to validate models before they are used in combustor design.

An example of such a comparison is shown in Figure 5, which is adapted from the recent Ph.D. thesis of Andrew T. Norris. This shows radial profiles in a methane/air turbulent jet diffusion flame. This is a challenging flow to simulate: the turbulent strain rates are sufficiently high that local extinction of the combustion reactions occurs. Nevertheless, as the figure shows, the model calculations agree well with the experimental data.

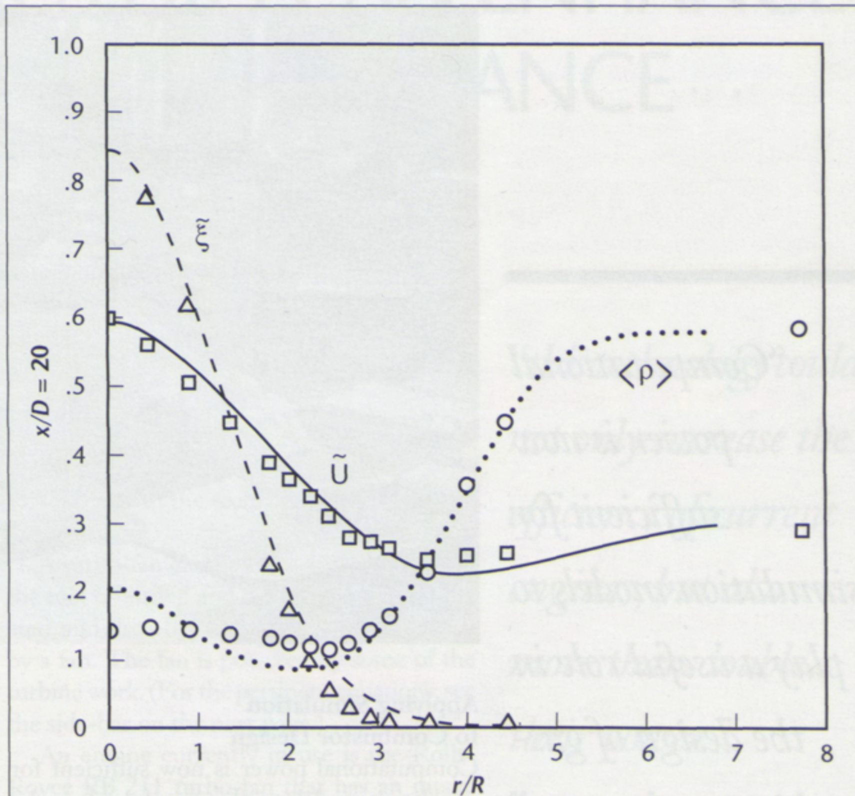
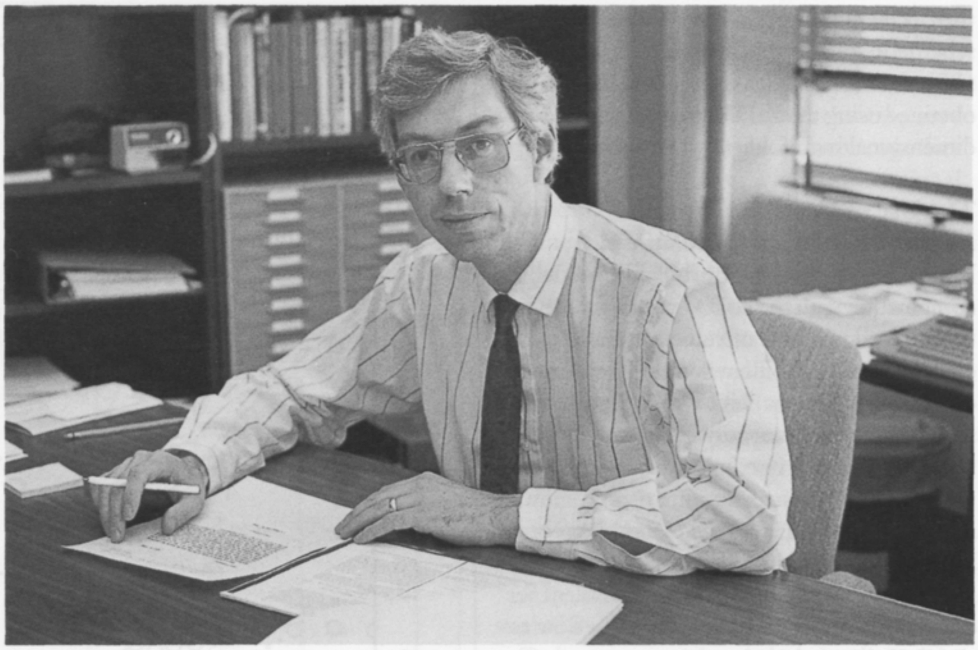


Figure 5. A comparison of simulation results with experimental data. The curves represent radial profiles of velocity, density, and mixture fraction in a methane/air turbulent jet diffusion flame at an axial distance of 20 nozzle diameters. The lines represent values calculated by the PDF simulation and the symbols represent experimental data.

The near field of a piloted jet diffusion flame. The central jet is pure fuel (methane) and the annulus that surrounds it is a pilot stream formed by many small premixed flames. A comparison of measurement and calculation for this type of flame twenty fuel-jet diameters downstream is shown in Figure 5.

"Computational power is now sufficient for simulation models to play a useful role in the design of gas-turbine combustors."



Applying Simulation to Combustor Design

Computational power is now sufficient for simulation models to play a useful role in the design of gas-turbine combustors. In fact, these methods are currently being used as part of the design process at General Electric, Allison Gas Turbine, and NASA Lewis.

As computers become more powerful, accessible, and affordable, the key questions concerning these models will be their scope and accuracy, rather than the computational cost that is entailed. In our work at Cornell we are continuing the development of accurate models of turbulence using PDF methods, and of combustion chemistry using the ILDM method. The gas-turbine combustors of the future will take shape and undergo testing on the computer before the actual prototypes are made and installed in real aircraft.

Stephen B. Pope is a professor in the Sibley School of Mechanical and Aerospace Engineering. The primary focus of his research is the development of computational procedures for calculating the properties of turbulent flows. He was educated at the Imperial College in London, where he received B.Sc., Ph.D., and D.Sc. degrees. Before joining the Cornell faculty in 1982, he conducted postdoctoral research at Imperial College, served as a research fellow in aeronautics in the Department of Applied Mathematics at the California Institute of Technology, and taught in the mechanical engineering department at the Massachusetts Institute of Technology. In 1990, he and two former graduate students won first prize in the IBM supercomputer competition for turbulence simulation performed at the Cornell Theory Center. Pope is a fellow of the American Physical Society, a member of the Combustion Institute, and an associate fellow of the American Institute of Aeronautics and Astronautics. In addition, he is an overseas fellow of Churchill College, at Cambridge University, and an associate editor of Physics of Fluids A.

HOW WAVE ROTORS CAN ENHANCE JET-ENGINE PERFORMANCE

by Edwin L. Resler, Jr.

A three-engine jet airliner could be flown on only one engine—without reducing the cruising speed—if a properly designed wave rotor were added between the compressor and turbine of the engine. At Cornell we have formulated a wave-rotor design procedure appropriate to tackle this and other tasks, and preliminary testing of the theory by NASA has given good results.

Increasing engine performance is a major challenge to aircraft designers. Currently, the most economical engines for aircraft are turbo fans, which are used on commercial jet airliners. Turbo fans have reduced the kinetic energy that is left behind in the white plumes following jet aircraft and created thrust from energy that otherwise would be wasted. But further improvement can be made.

Our work, carried out with the support and cooperation of scientists at the NASA Lewis Research Center, began with the fundamentals of rotor design and has progressed through experimental confirmation of a design procedure. The indications are that this technology could not only increase the efficiency of current engines, but also more than double their power.

"this technology could not only increase the efficiency of current engines, but also more than double their power."

Current Technology for Turbo-Fan Engines

We begin with the technology of current jet engines.

A turbo-fan engine has a core flow where the fuel is burned and turbine work is generated, and also a bypass flow that is compressed by a fan. The fan is powered by some of the turbine work. (For the pertinent equations, see the side-bar on the next page.)

An engine currently in use is the Rolls-Royce RB 211 turbo-fan that has an intake diameter of 102 inches and a bypass ratio of 4.7. Three of these engines power the 430,000-pound Lockheed 1011, which cruises at 35,000 feet—where the pressure is 0.24 atmosphere and the temperature is –60° F—at a Mach number (the ratio of aircraft speed to atmo-

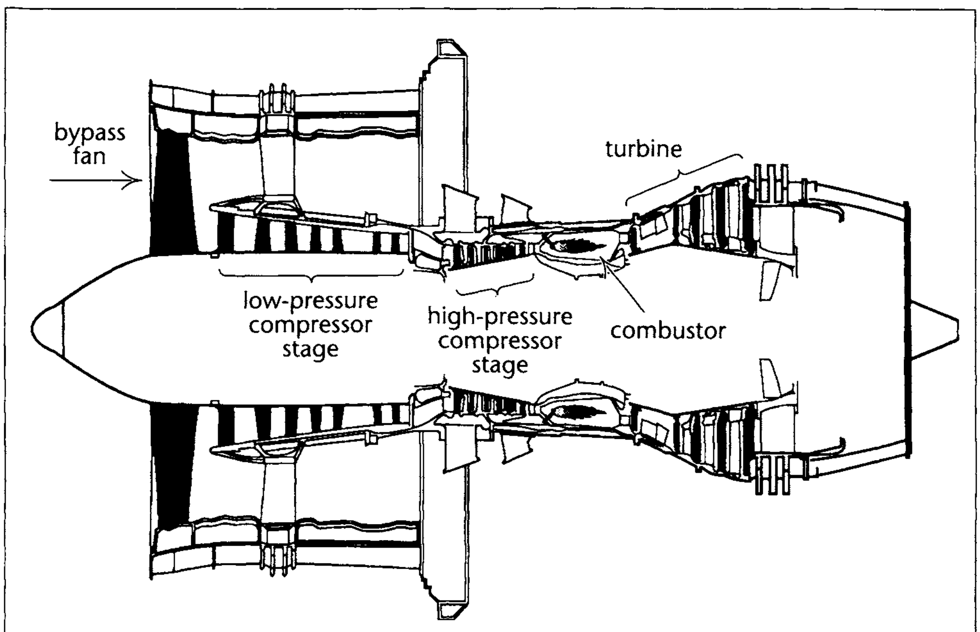


Figure 1. A schematic diagram of a Rolls-Royce RB-211 turbo-fan engine. The turbine blades at the exit of the combustor are subjected to the peak cycle temperature. The material limitation of these blades limits the performance of conventional gas turbine engines.

The Mathematics of Jet Engine Enhancement

The energy entering the nacelle plus the heat released by burning the fuel equals the energy leaving the nacelle:

$$h_f + \tfrac{1}{2}u_f^2 + q = h_x = \tfrac{1}{2}u_x^2 \qquad [1]$$

or

$$\tfrac{1}{2}u_x^2 - \tfrac{1}{2}u_f^2 = q - (h_x - h_f) \qquad [2]$$

where u is the velocity relative to the nacelle, h is the enthalpy, and q is the heat added to a unit mass flowing through the engine by the fuel. The subscript f denotes the flight conditions ahead of the aircraft and the x subscript denotes the flow conditions at the engine exit.

Now consider the air being processed by the engine. It is an "open cycle," whatever it might be. To close the "open cycle," a constant pressure process is appropriate, in which case $(h_x - h_f)$ is the cycle's rejected heat (q_r). Using a cycle energy balance, $q - q_r = \textit{cycle work} = \eta_{cycle}q$, where η is efficiency, we find that for jet propulsion systems exhausting at flight pressure, for any cycle:

$$\tfrac{1}{2}u_x^2 - \tfrac{1}{2}u_f^2 = \eta_{cycle}q \qquad [3]$$

A turbojet has a core flow where the fuel is burned—and therefore is governed by the above equation—and a bypass flow compressed by a fan that is powered by part of the cycle work generated by the core flow. Thus the total mass flow, m, through the engine is made up of the core flow, m_{core}, and the fan flow, m_{fan}, so that

$$m = m_{core} + m_{fan} \qquad [4]$$

The thrust force of the turbofan or turbojet is, in this case, $F = m(u_x - u_f)$, and the "core flow work" is utilized to power the fan flow as well as the core flow. If it is assumed that the core and fan flow have the same exit velocity, u_x, this can be summarized for a 100-percent-efficient fan in the formula:

$$m(\tfrac{1}{2}u_x^2 - \tfrac{1}{2}u_f^2) = m_{core}\eta_{cycle}q \qquad [5]$$

If we factor this equation and use our expression for the thrust, F, and use the propulsive efficiency, η_{prop}, defined by

$$\eta_{prop} = \frac{2}{1 + (u_x/u_f)} \qquad [6]$$

we find, after some rearrangement, the following equation:

$$Fu_f = m_{core}\eta_{prop}\eta_{cycle}q \qquad [7]$$

It is useful to introduce the equivalence ratio ϕ, defined as the operating fuel-to-air ratio divided by the stoichiometric fuel-to-air ratio. For jet fuels (essentially kerosene) the stoichiometric fuel-to-air ratio is taken to be 1/15, and furthermore,

$$q = \left(\frac{\text{lb. of fuel}}{\text{lb. of air}}\right) \times \text{(fuel heating value) or}$$

$$q = \phi \times \left(\frac{\text{lb. of fuel}}{\text{lb. of air}}\right)_{\text{stoichiometric}} \times \text{(fuel heating value).}$$

Using $m_{core} = \rho_f u_f A_{f,core}$, where ρ_f is the density at flight altitude and $A_{f,core}$ is the area of the free streamline containing the core flow ahead of the engine nacelle, and a fuel heating value of 18,000 B.T.U. per pound of fuel, and then the gas law to eliminate the density in favor of the pressure and temperature, and further recognizing that at aircraft cruise altitudes the temperature is 400° Rankine, we write our last equation in the convenient form

$$\boldsymbol{F = 43.3\,(\phi\eta_{prop}\eta_{cycle})\,p_f A_{f,core}} \qquad [8]$$

This equation is convenient in that the dimensionless quantities in the parenthesis can each at most be 1, indicating peak thrust for any engine at an altitude where the pressure is p_f.

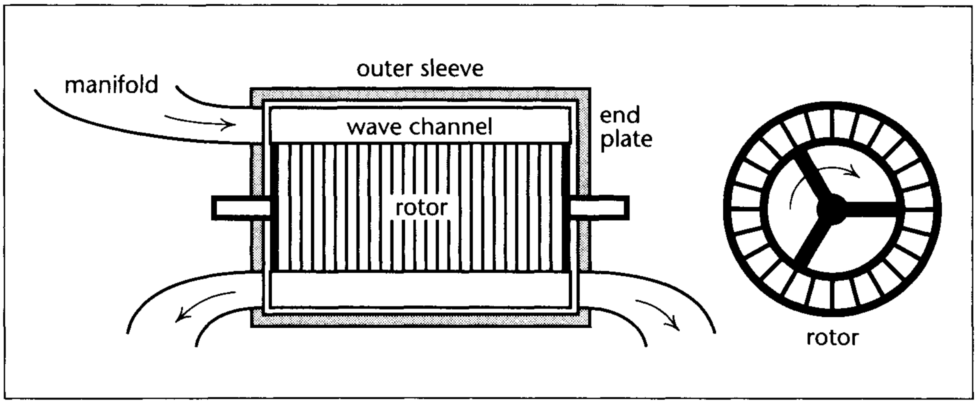


Figure 2. A wave rotor, made up of a multitude of channels arranged around a cylinder that is rotating at a constant speed. Situated between the compressor and the turbine of a conventional engine, this addition permits the same engine components to produce greater thrust more efficiently by utilizing wave action in the channels.

spheric sound speed) of 0.85. At cruise each engine supplies 9,400 pounds of thrust. The specific fuel consumption of this aircraft has been measured at 0.64 pounds of fuel per pound of thrust per hour. These data are sufficient to calculate the three quantities that summarize the performance of this engine: $\phi = 0.13$, $\eta_{prop} = 0.86$, and $\eta_{cycle} = 0.39$. (As defined in the side-bar, ϕ is the operating fuel-to-air ratio divided by the stoichiometric fuel-to-air ratio, and η denotes efficiency.) Note that the value of ϕ is very low compared to the value of 1, which is where automobile engines operate.

The performance of the components of this engine can be estimated. Since the fuel consumption gives the heat added to the thermodynamic cycle and the flight and exit velocities determine the work of the cycle, the rejected heat and therefore the temperature of the core flow can be determined. In our case, the core flow is found to exit the nacelle at 325 °F. A turbine efficiency of 91percent and a temperature out of the combustor (or into the turbine) of a comfortable 1,700 °F would result in a compressor operating at a pressure ratio of 42 with an efficiency of 82 percent.

Prospects for Engine Improvements

Suppose we desire to use only one engine, and propose to accomplish this feat by adding more fuel to a single existing engine. We assume that the front of the engine—namely, the compressor—operates as described above and that the turbine will operate at the same efficiency as before. We find that for the same aircraft performance $\phi = 0.36$, $\eta_{prop} = 0.67$, and $\eta_{cycle} = 0.55$, and that the specific fuel consumption has decreased to 0.60 pounds of fuel per pound of thrust per hour. All of the three "changeable" design parameters have changed, but their product, which determines the overall performance, has tripled. Since the only modification has been the amount of fuel burned in the same engine, why is this change not instituted?

A closer look at the calculation reveals that the turbine inlet temperature has risen to a formidable 2,821°F, very close to the melting point of the blade material. In the past, major improvements in jet-engine technology have depended on, and followed, the development of turbine-blade materials that could withstand higher temperatures. Currently, turbine blades are fabricated from perfect crystals and protected by a layer of cooling air from the compressor. But although the materials technology continues to advance, progress is becoming more difficult. Wave-rotor technology offers another approach to solve this problem.

The Development of Wave-Rotor Technology

A wave rotor is a rotating cylindrical bundle of channels that guide waves and gases along their length (see Figure 2). The waves and gases are driven by flows introduced through ports at the ends of the channels. Engine performance can be improved in this case by situating a wave rotor after the compressor and before the turbine of the conventional engine. Wave motion in the rotor replaces the turbine parts that are impossible to fabricate to withstand the high temperatures; and shock-wave compressions, driven by the expansion of gas

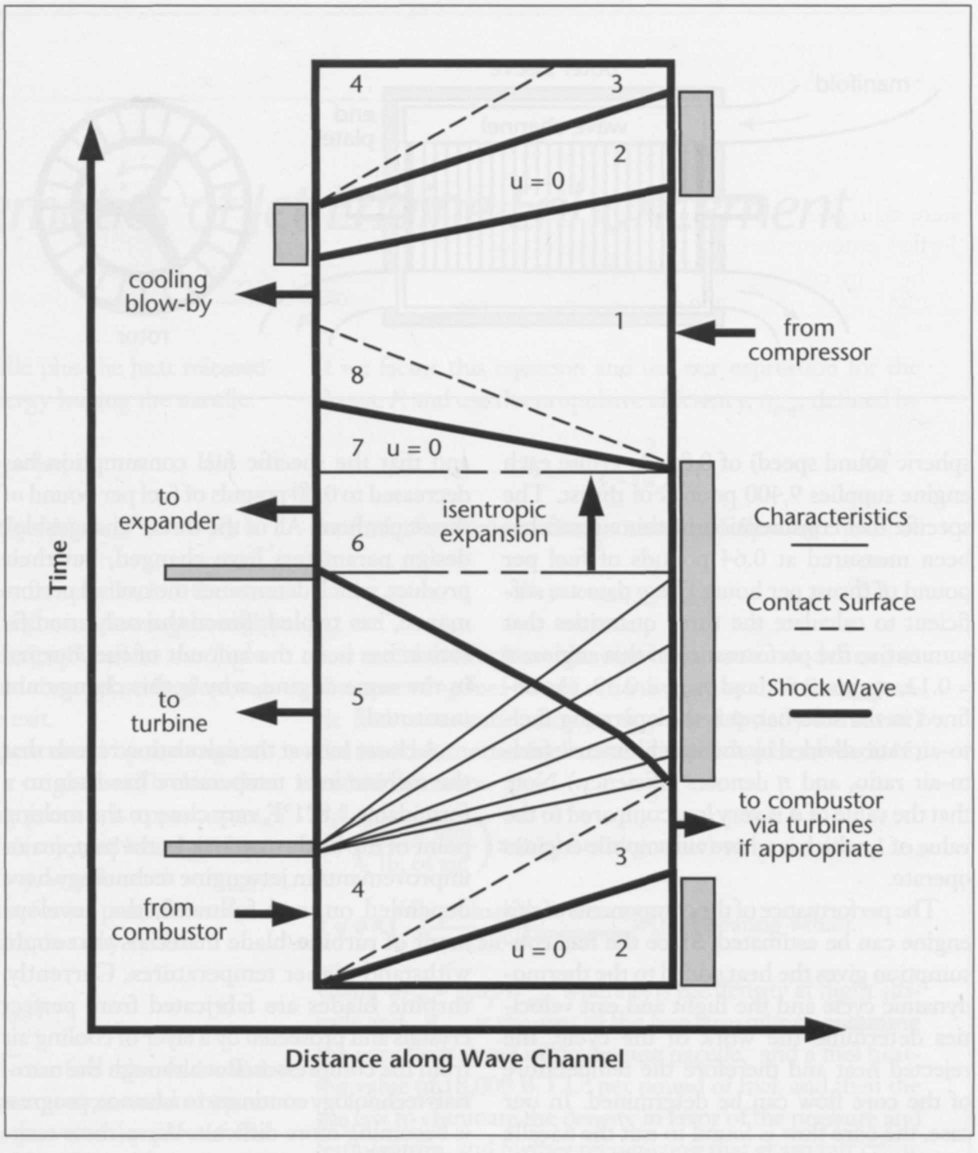
Figure 3. A MINQ wave diagram, showing the essential features of wave action in the channels of a rotor.

What are called waves (in accordance with popular usage) are, more precisely, the mathematical characteristics of the set of differential equations describing the conservation laws for the one-dimensional flow in the rotor channels. There are two types of waves in a channel—those moving with velocity ($u+a$) and those moving with velocity ($u-a$), where u is the flow speed in the channel and a is the local sound speed. These are called P and Q waves, respectively.

The eight regions of the cycle are numbered in this figure. Gas from the engine compressor enters region 1 at sound speed to trap P waves in the channel and sweep out the residual gases from the previous cycle. The blow-by section makes it possibile to use compressor gas for cooling.

Next, the flow is stopped and compressed by the shock wave from a plate at the end of the channel. The gas in region 2 then encounters another shock wave (2 to 3) which is produced when the plate that stopped the flow ends, and hot, high-pressure combustion gas is introduced into the wave channel at the left side. The shock-compressed gases (region 3) are then collected and directed to the combustor.

Closing port 4 and opening port 5 to a lower pressure causes an unsteady expansion wave to cool and exhaust the combustion gases to a turbine. The flow out of port 5 is uniform until the wave created by closing port 3 traverses the channel. The flow in the channel from 6 to 7 is isentropic, and the pressure at 7 is chosen to produce the shock wave that is required to flush the channel and prepare it for another wave cycle.



when heated in a combustor at constant pressure, replace the corresponding compressor section.

Although there is an unsteady wave motion in each channel, the flow issuing from the ports at any circumferential position is steady. A particular cycle chosen and tailored for the application under discussion is of the MINQ type. This cycle starts with the introduction of air from the conventional compressor and is made up of eight identifiable parts (see Figure 3). The wave compression is accomplished with two shock waves before introduction of the gases to the combustor. Completion of the wave cycle requires complementary expansion waves, as indicated. The cycle also includes the provision for blow-by to cool the rotor or associated hardware. The cycling of the hot and cold gases results in a low average temperature of the metal parts, in this respect mimicking the automobile engine, in which combustion occurs at $\phi = 1$.

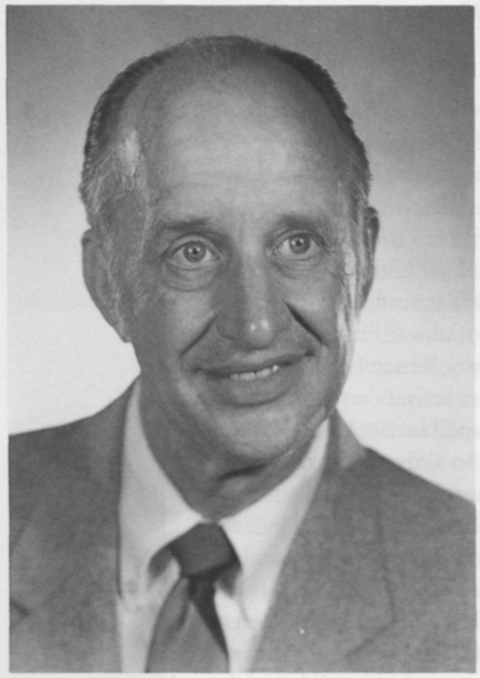
The addition of the wave rotor to the present engine configuration results in the desired performance: the thrust is tripled, the specific fuel consumption is reduced to 0.60 (the same as was calculated for the single engine without the wave rotor), and the turbine inlet temperature is not too high. In the calculations, it is assumed that the components have comparable efficiencies. The average temperature of the gas out of the rotor and into the turbine, after being cooled by the expansion, is 2,099 °F, as compared to the 2,821 °F that was calculated for this temperature in the absence of the wave rotor. The parameters determining performance are $\phi = 0.37$, $\eta_{prop} = 0.62$, and $\eta_{cycle} = 0.58$. Furthermore, in this case there is no cooling blow-by. If 29 percent of the flow entering the combustor were utilized for blow-by cooling, the "out temperature" would be reduced to 1,700 °F without affecting performance.

The Promise of Wave-Rotor Technology

In this article I have presented a brief discussion of the principles that can be employed to dramatically improve the performance of jet engines. The application of this technology to propulsion in general is much broader than the special case discussed in this brief note. Other possibilities under active investigation are the use of wave rotors for supersonic flight and their use to control NO_x emission, thereby permitting flight at altitudes adjacent to the ozone layer.

Since 1989, research personnel at the NASA Lewis Research Center, Cornell, and other centers have cooperated to systematically explore the possibilities of this approach to engine design, and to verify experimentally the theoretical predictions. The first experimental confirmation of the usefulness of the theoretical predictions developed at Cornell and NASA was accomplished last summer. The experiments continue and will be used to fine-tune the design procedures.

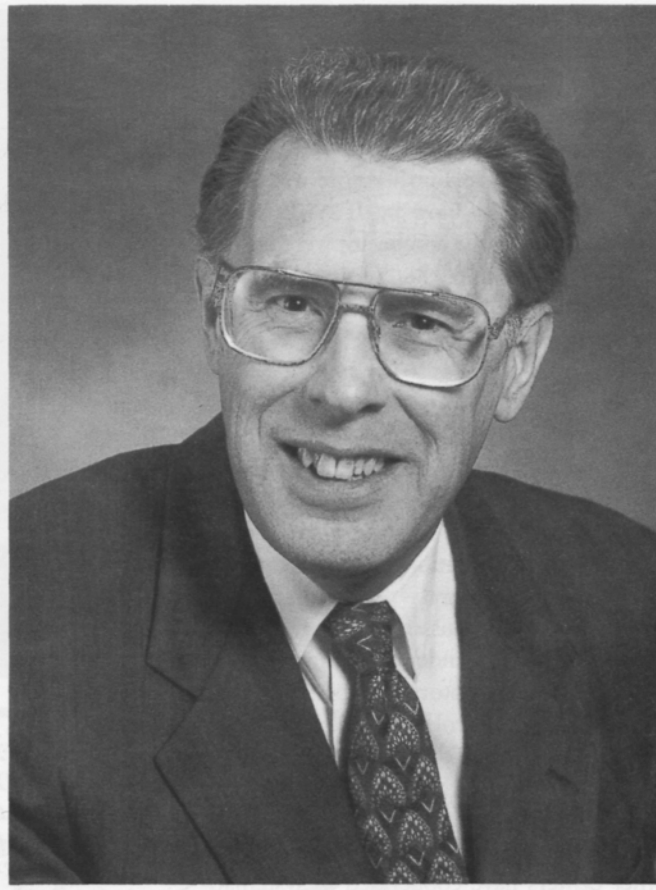
While the replacement of three of the engines on a modern wide body transport by only one of the same size is admittedly optimistic, if the three are eventually replaced by only two, the research effort in wave-rotor technology will have been well worthwhile.



Edwin L. Resler, Jr. is the Joseph Newton Pew, Jr. Professor of Engineering, Emeritus. He received the Ph.D. from Cornell in 1951 and has remained at the university throughout his career except for four years at the University of Maryland (1952–56). He was involved in the early design of wave engines, shock-tube research, and magnetohydrodynamics; he helped minimize the sonic boom in aircraft and air pollution from automobile engines. He has been a consultant to many industries, and has spent sabbatical leaves at AVCO Corporation's Research and Advanced Development Division, Pratt and Whitney's Advanced Engine Design Group, and the Propulsion Systems Division of NASA's Lewis Research Center. He is a member of the American Physical Society and a fellow of the American Institute of Aeronautics and Astronautics (AIAA). He has been an editor of Astronautics, *the* AIAA Journal, *and* Physics of Fluids, *as well as director of the Sibley School of Mechanical and Aerospace Engineering.*

"Other possibilities under active investigation are the use of wave rotors for supersonic flight and their use to control NO_x emission"

John E. Hopcroft Named Dean



As of January 1, 1994, the College of Engineering has a new dean. A search that began after William B. Streett announced his intention to resign, in June 1993, had no trouble choosing, from a field of well-qualified candidates, the best man for the job: John E. Hopcroft.

Since July 1992, Hopcroft has been associate dean for college affairs. The administrative ability he demonstrated in that position soon convinced many members of the faculty and staff that he should be the next dean of the college.

Hopcroft's career is a record of continual progress through hard work, with no wasted motion. Close observers report that he is "incredibly focused," with the ability to quickly master the details of a problem, analyze it clearly, and make an appropriate decision. He is also said to be a good listener, and good at delegating responsibility to talented associates. He is not naturally gregarious, but he has systematically built up a wide-ranging network of contacts through his service to professional organizations and to the college.

Hopcroft is a computer scientist who was trained, before there were departments of computer science, in electrical engineering. He received the bachelor's degree from Seattle University in 1961, and the Ph.D. from Stanford University in 1964. His first academic appointment was at Princeton University, where he spent three years before coming to Cornell in 1967.

An active researcher in the general area of modeling and simulation, Hopcroft has worked to delineate a set of fundamental principles that underlie real-world systems. This is important for object representation, solid modeling, graphics, and automated design. He has guided the research of nearly thirty doctoral candidates, and been an author or editor of five books and more than eighty academic papers. He has been invited to give lectures all over the world.

In addition to his academic duties, Hopcroft has spent considerable time and energy in service to his profession. He is a referee for nine journals, and has been an editor or associate editor of seven. He belongs to the Association for Computing Machinery, the Society for Industrial and Applied Mathematics, the American Association for the Advancement of Science, the New York Academy of Science, and the Institute of Electrical and Electronics Engineers. He has been a member of many committees established by these organizations, as well as by other institutions. In 1992, President Bush appointed him to the National Science Board, which oversees the National Science Foundation.

Hopcroft has also been unstinting in his service to Cornell. He was graduate field representative for the Department of Computer Science from 1968 through 1975, and has been a member of numerous committees. He was appointed chair of his department in 1987, and he served in that capacity until he became associate dean of the college.

The honors that have been bestowed on Hopcroft reflect his extraordinary accomplishments. He was named to an endowed chair, becoming the Joseph C. Ford Professor of Computer Science, in 1985. The next year, he was a co-winner of the A. M. Turing Award, which is given by the Association for Computer Machinery and is regarded as the most prestigious award in the field. In 1987 he was made a fellow of the American Academy of Arts and Sciences, the American Association for the Advancement of Science, and the Institute of Electrical and Electronics Engineers. In 1989 he was elected to membership in the National Academy of Engineering, and in 1990 his alma mater, Seattle University, awarded him an honorary degree.

On the occasion of

Hopcroft's appointment as Joseph Silbert Dean of Engineering, Frank H. T. Rhodes, president of Cornell University, praised him as "a man of vision, a first-rate educator, and an outstanding computer scientist."

Hopcroft's vision for the college is, typically, perfectly clear. "I believe that the highest priority for the college is maintaining the excellence of its faculty, since it is they who will, in the long run, determine our identity and our priorities as an institution," he has written. This requires not only wise decisions with regard to hiring and promotion, but also the maintenance of an environment that is conducive to optimal performance.

Hopcroft believes that the college's mission to educate young engineers is best carried out in the context of front-line research. "As a leading research institution," he has written, "the college provides students with the unique educational opportunity of being introduced to subject matter by top researchers and scholars." Not only do faculty members present what is already known, but they also "expose students to the processes of extending the boundaries of knowledge."

"To work with the faculty and staff to help shape the direction of the engineering college is," Hopcroft says, "the opportunity of a lifetime."

The Streett Years: Humanizing Engineering

When William B. Streett stepped down, he had led the College of Engineering for a longer time than any other dean since Solomon Cady Hollister (1937–59). He became acting dean in 1984, when Thomas E. Everhart left to become chancellor of the University of Illinois at Urbana, was appointed dean in his own right the following year, and remained in the post through the end of 1993.

Having resigned the deanship so that he can devote more time to family responsibilities, Streett will resume teaching and research activities in the School of Chemical Engineering. He is an experimentalist, concerned with the physical and thermodynamic properties of dense fluids. His careful work, designing equipment, building it, and using it to take precise measurements, has resulted in more than 120 publications. The work is not glamorous, but the results are important both to theorists who are interested in predicting the properties of fluids and to engineers who want to design chemical processes.

Without the administration of the college on his shoulders, Streett will also have more time for his hobbies, history and cabinetmaking. He has long been interested in the relationship between society and technology, and in recent years he has studied the history of engineering education. He also builds mission-style furniture from quarter-sawn oak. He can look at a picture of a desk, draw up a detailed pattern, and then use the pattern to make the desk.

Streett's background is in the military. He received a bachelor's degree from West Point and served in the U.S. Army for twenty-three years. During this time, he earned a doctorate in mechanical engineering at the University of Michigan, and then returned to West Point, where he spent fifteen years on the faculty. In 1978, he retired from the service with the rank of colonel and came to Cornell. At first he was a senior research associate, but in three years he became a full professor and was appointed associate dean for research and graduate study.

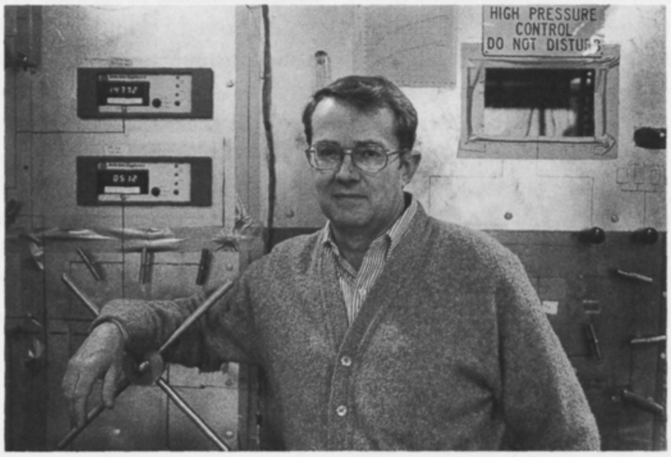
Some staff members were nervous when Streett was named to succeed Everhart, fearing that the college's administration would take an authoritarian turn under the leadership of a man with a military background. But this was not to happen. Streett

turned out to be, more than anything, a craftsman and a humanitarian.

The patient pursuit of pragmatic goals marked much of Streett's term of office, which bridged one of the most momentous events of recent times: the end of the Cold War. Initially, he developed a "master plan" to revitalize the college's infrastructure. This ambitious project would have surrounded the engineering quad with new and improved buildings. And a part of this construction program was carried out; Olin Hall was thoroughly remodeled, two floors were added to Upson Hall, and the Engineering and Theory Center Building was erected.

But when the Soviet bloc collapsed, Streett immediately saw how this change in the world order would affect the College of Engineering. For forty-five years, fear of communist expansion had led to federal expenditures for every kind of research that might have implications, however indirect, for national defense. Before the Cold War, engineering colleges had concentrated on training good engineers, and when the Berlin Wall came tumbling down, Streett decided that this had better become a priority once again. "In the future," he said in a recent interview, "universities will be judged not only on the quality of their research and graduate programs, but increasingly on how well they prepare young women and men, at the undergraduate level, to go out and address the technological, economic, social, and cultural problems that confront our society."

Streett realized that engineering, as a profession, had arisen in the eighteenth and nineteenth centuries to meet the needs of the military, and that engineering education had remained a kind of boot camp. He also realized that a person does not have to be tough as nails to be a good engineer, and that women and underrepresented minorities must be drawn into the profession. So he set about humanizing the college and the curriculum. He asked all faculty members, regardless of rank, to serve as advisors, and he instituted a one-credit freshman course that brought students and their advisors together once a week so that they could get to know each other. He presided over the breaking up of large, impersonal introductory courses into small sections where students could get a larger measure of individual attention. He instituted a communications program, to help engineers develop better writing and speaking skills. He set up an office to deal with the special problems that women must confront as they enter a profession that has previously been a male preserve. He established annual awards to recognize those who excel in teaching and advising, and he urged the donors of new endowed chairs to make excellence in teaching a prerequisite for appointment to these professorships.



"We must continue to challenge our students through a rigorous and demanding program," Street has said, "but we must also reach out to them and help them feel connected. That has not been a tradition in engineering, but it has to become one."

It is a tradition that is now well underway, having been crafted patiently, one step at a time, during Streett's years as dean.—DP

Current research activities in the Cornell College of Engineering are represented by the following publications and conference papers that appeared or were presented during the four-month period May through August 1993. (Earlier entries omitted from previous Quarterly *listings are included here with the year of publication in parentheses.) The names of Cornell personnel are in italics.*

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Selker, J. S., L. Graff, and *T. S. Steenhuis*. 1993. Non-invasive time domain reflectometry moisture measurement probe. *Soil Science Society of America Journal* 57:934–36.

Surface, J. M., J. H. Peverly, T. S. Steenhuis, and *W. E. Sanford*. 1993. Effect of season, substrate composition, and plant growth on landfill leachate treatment in a constructed wetland. In *Constructed wetlands for water quality improvement*, ed. G. A. Moshiri, pp. 461–72. Boca Raton, FL: Lewis Publishers.

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Moeckly, B. H., and *R. A. Buhrman*. 1993. Electromigration studies of the role of oxygen defects in $YBa_2Cu_3O_{7-\delta}$ grain boundary weak links. *IEEE Transactions on Superconductivity* 3:2038.

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