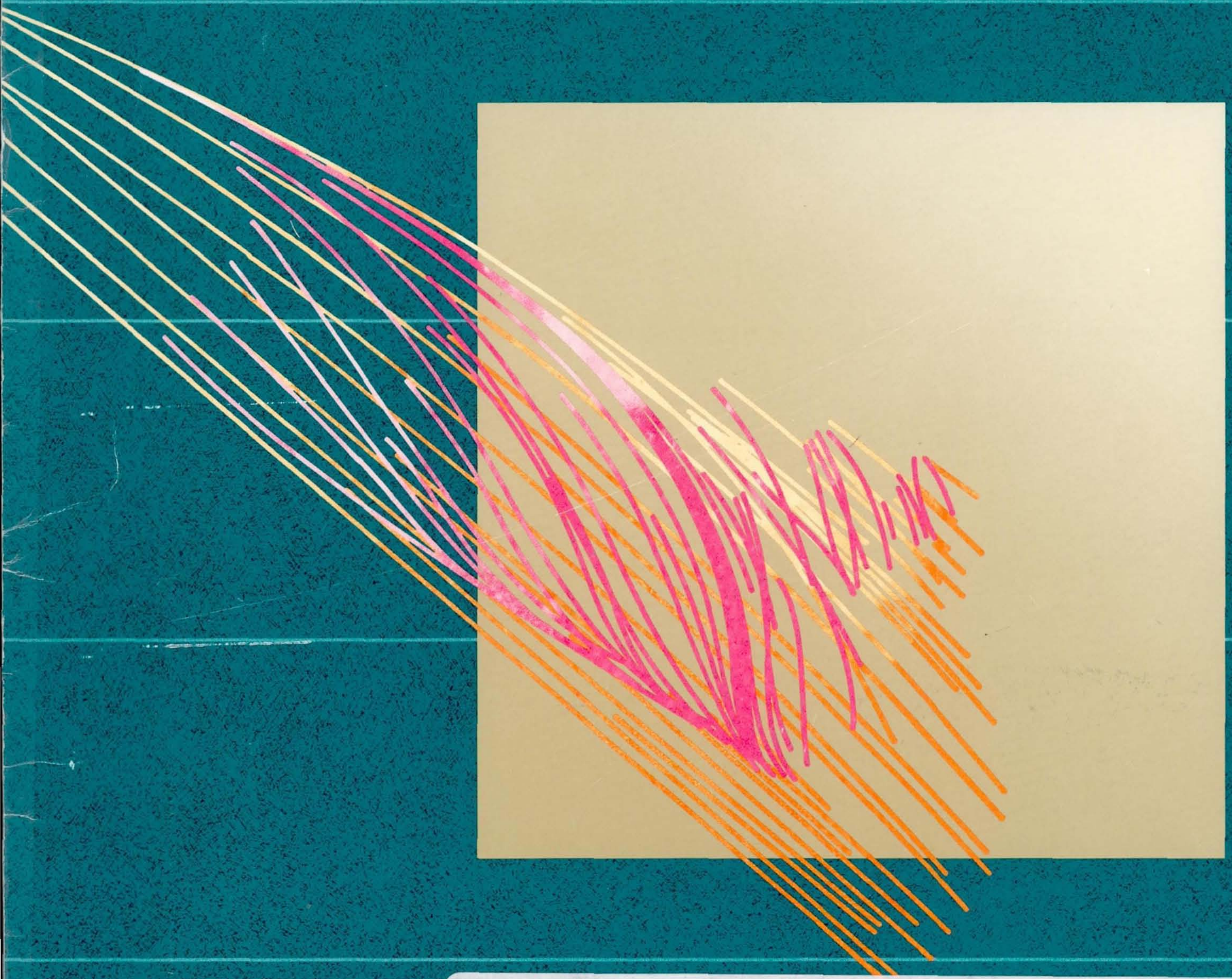
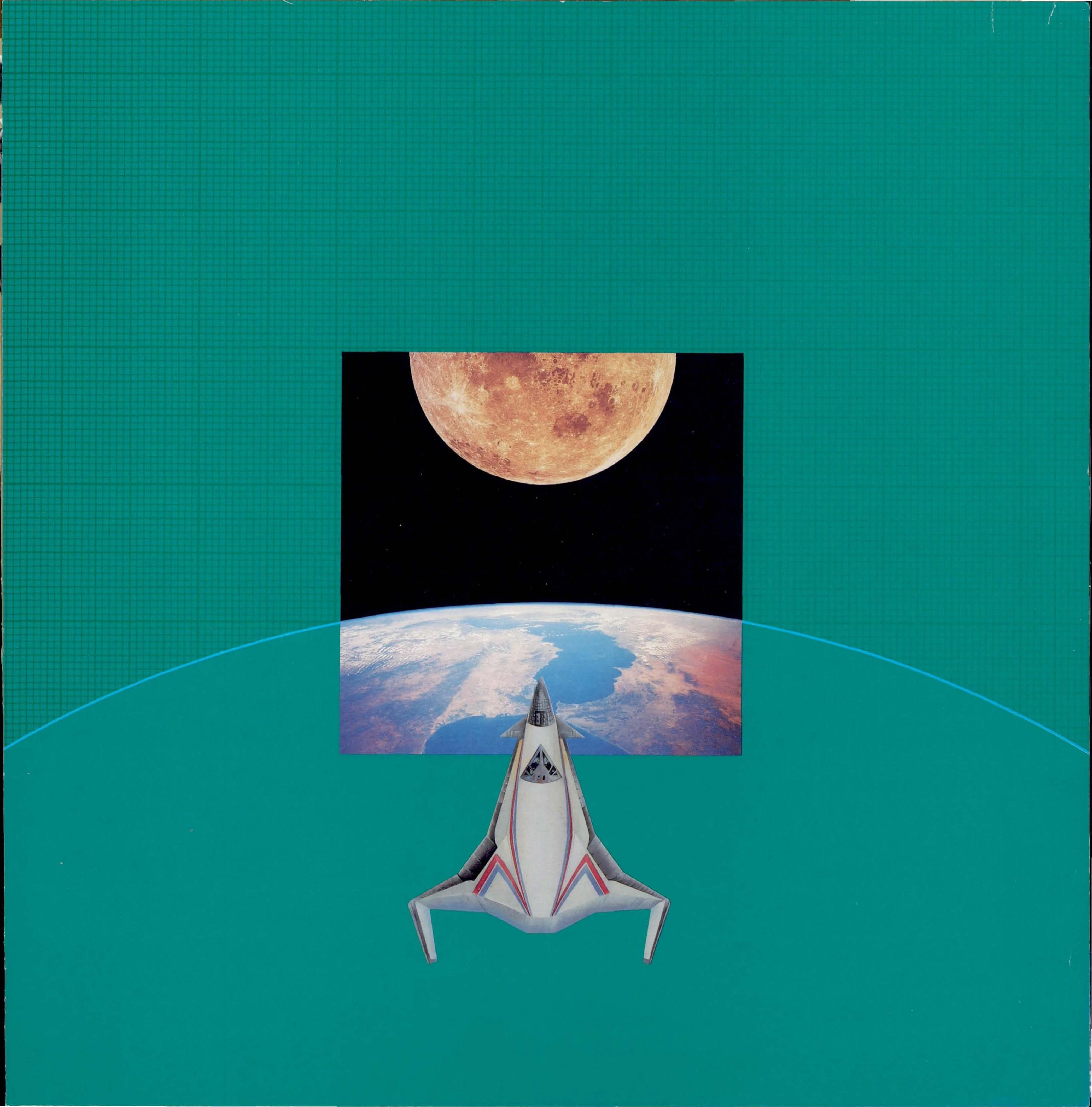


NASA

NUMERICAL AERODYNAMIC SIMULATION

TO THOSE WHO DEVOTE THEIR LIVES
TO THE PURSUIT OF KNOWLEDGE FOR THE
ENRICHMENT OF MANKIND

NUMERICAL AERODYNAMIC SIMULATION



Since the very beginnings of flight, man has relied on testing and development of new concepts before taking the final steps of full scale design and implementation. Nearly all great technical advances are the product of innovative minds leveraged by the machines they invent to help them realize their dreams. The first step, the "Wright Flyer," was the result of many hours of scale model testing in an early wind tunnel, accompanied by unpowered experimental glider flights.

The rapid advance of the aeronautical sciences continues in much the same way. From the early days of barnstorming developments through the formal establishment of an agency to support aeronautical research and development, progress has always been tied to advances in supporting technology areas. Today, the advanced tools that have been created to fuel this growth are computational fluid dynamics (CFD) and ultramodern supercomputers.

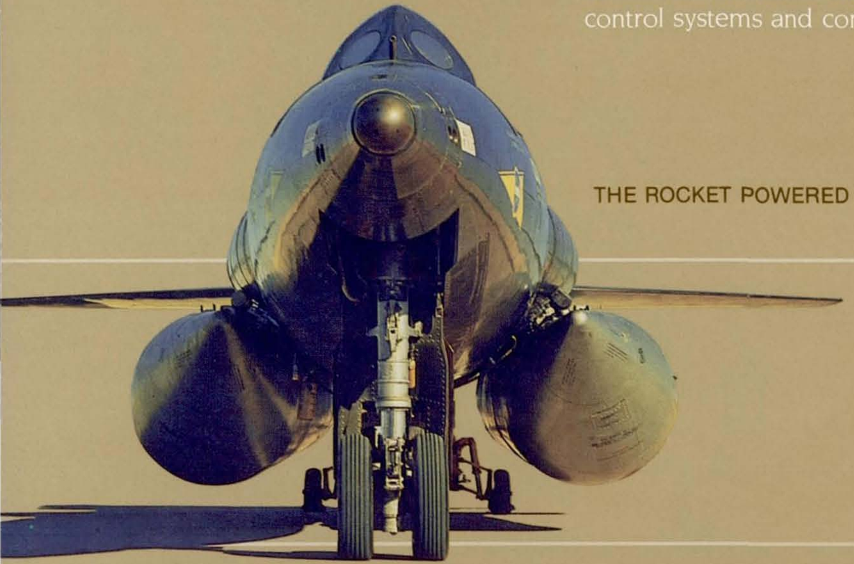
A productive bond has formed between these advanced sciences. This has led to an improved understanding of fluid physics and the interdisciplinary ties between aerodynamics and the thermal and chemical phenomena associated with the extended limits of modern flight. Computers support evaluations of design configurations and flight conditions that cannot be treated in other ways and numerical simulation complements and extends data obtained from wind tunnels and other experimental facilities.

Contemporary aircraft bear the imprint of the computer age. The pilot and aircraft communicate through complex control systems and computers. Everything must work together in closely timed harmony as aerodynamic shapes undergo dynamic revision and environments shift rapidly during flight. Computerized flight control systems are essential to many highly maneuverable, but otherwise basically unstable, aircraft.

National progress and economic advantage hinge on the use of the most advanced technologies to support pioneering activities. Aeronautics has always been an area in which the most creative talents were employed in the quests for new ideas. Pathfinding efforts will continue with aerodynamic sciences linked inseparably to the computer.

GLIDER TESTS
PRECEDE THE "WRIGHT FLYER"

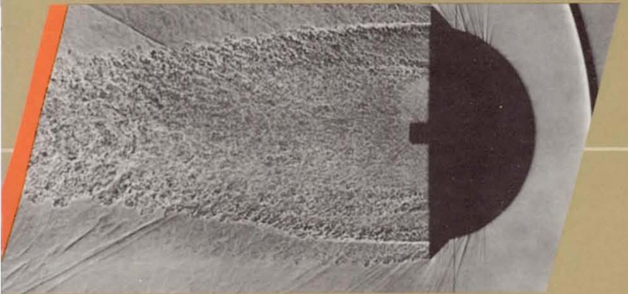
FIRST MEETING OF THE NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS 1915



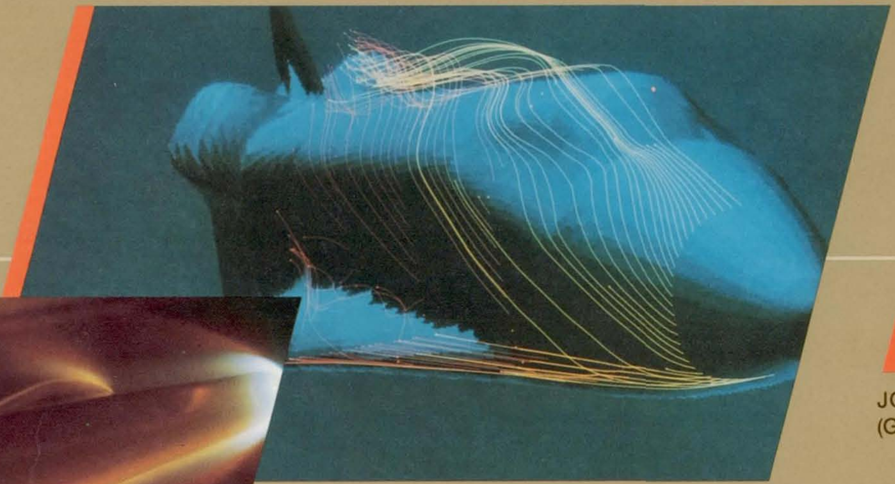
THE ROCKET POWERED X-15

BOEING 707

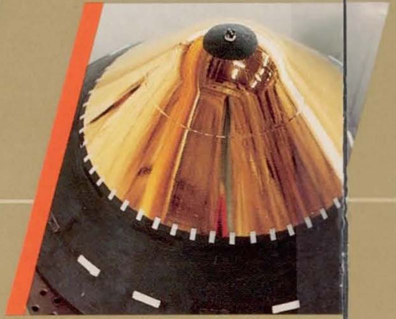
ENTRY BALLISTICS ON A BLUNT BODY



LIFTING BODY
UNDERGOING WIND TUNNEL TESTING



COMPUTED SPACE SHUTTLE FLOW FIELD



JOVIAN ATMOSPHERIC PROBE (GALILEO) HEAT SHIELD

THE COWLING
FIRST OF THE NACA CONTRIBUTIONS

DOUGLAS DC-3

KOREAN WAR JET FIGHTER
THE BANSHEE

X-1 BREAKS THE SOUND BARRIER

COMPUTATIONAL FLUID DYNAMICS BEGINS
USING THE ILLIAC IV COMPUTER

NORTH AMERICAN XB-70
SUPERSONIC TRANSPORT

THE X-29
EXPERIMENTAL FORWARD SWEPT WING AIRCRAFT

THE FUTURE NATIONAL AEROSPACE PLANE (NASP)

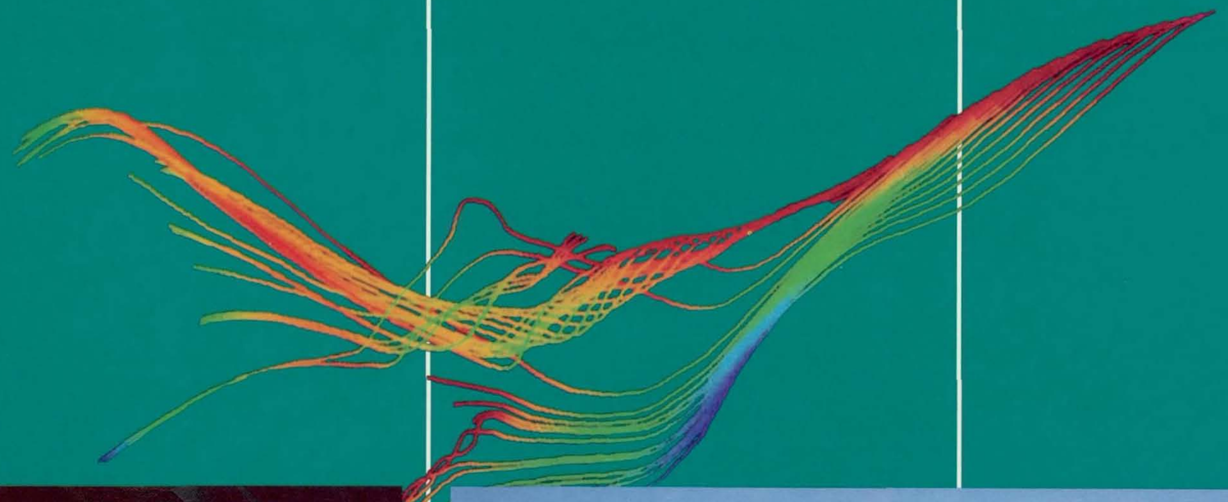
The use of computational fluid dynamics in modern aircraft design is a dream that has become a reality. Past aeronautical developments could not explore all of the dimensions of fluid mechanics during the design process. Numerical Aerodynamic Simulation (NAS) establishes the capability to conduct modern design explorations using the most advanced computers.

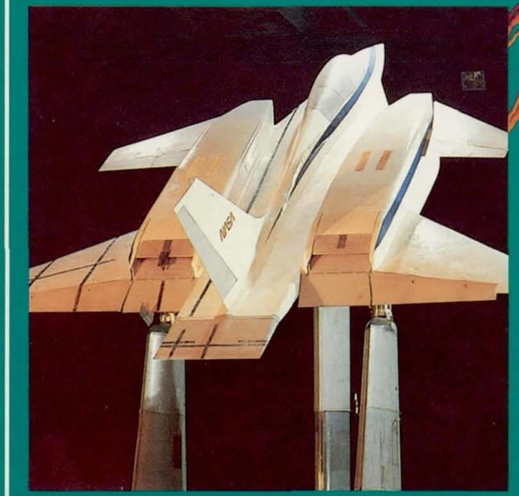
Opportunities for the advancement of U.S. leadership in aeronautics are immutably tied to exploitation of the science of computational fluid dynamics. The tempo of aeronautical research and design has increased dramatically in the United States. The scope of problems and applications that can now be addressed continue to surpass technology projections.

The supercomputer is a time machine. Design iterations that formerly required years of development with wind tunnels and experimental flight tests can now be completed on compressed time scales. Today, wind tunnel and experimental flight tests assume a new, more confident and productive role. Wind tunnels evaluate models at a mature stage of design and are used to verify and improve numerical codes. Flight testing can proceed with more confidence due to the range and extent of dynamic simulations that have been provided by the computer.

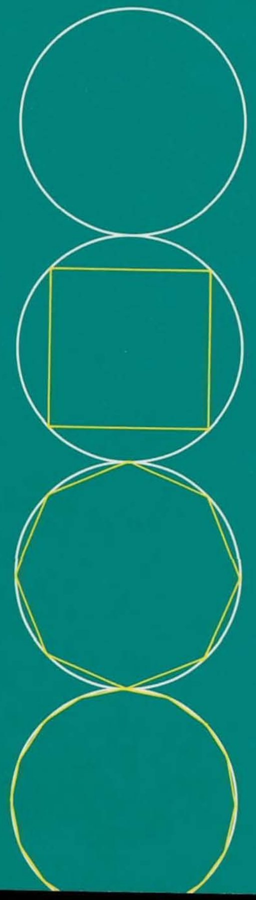
The long range goal of CFD is to develop software tools that will compute, in a few minutes, the actual viscous flows around realistic computational models of aircraft and aerospace vehicles. This capability will simulate localized flow phenomena as well as define the stability and control, performance and loads for complete systems, including aircraft, helicopters, missiles and spacecraft. Increased understanding of these phenomena will result in advanced vehicle designs with substantially improved performance and efficiency.

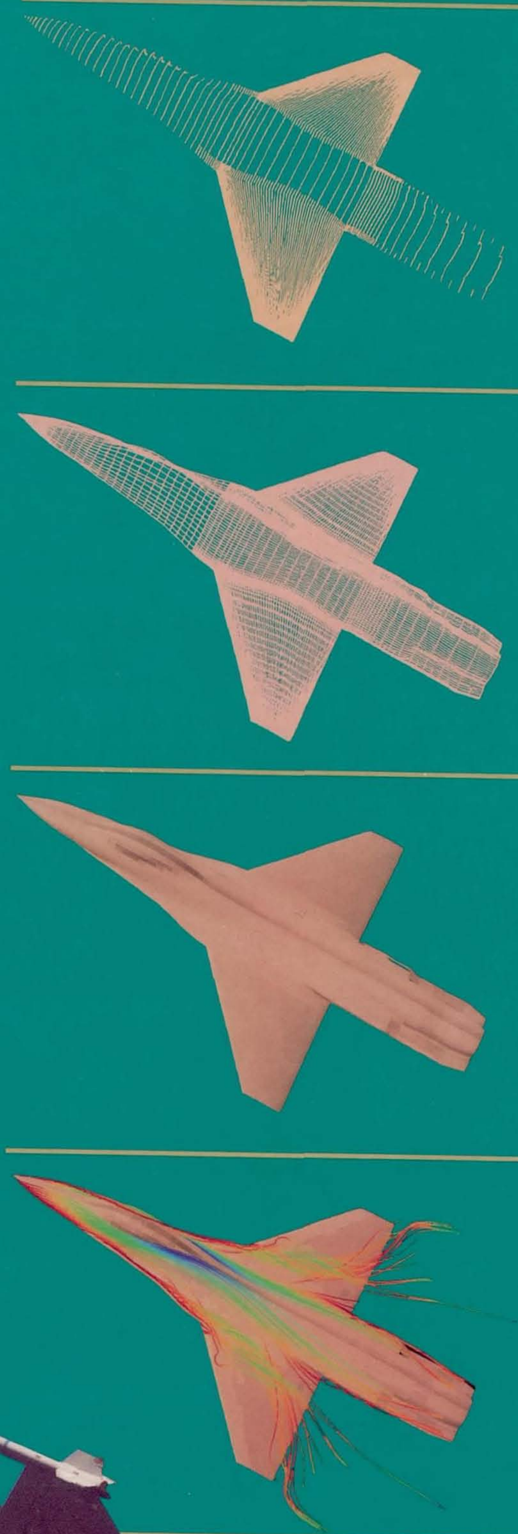
NAS is a national resource available to support research and development for commercial and military aircraft. Designs can now be modeled with very high fidelity. Design revisions can be evaluated on time scales that were unheard of only a decade ago. Implementation of fluid dynamics algorithms, once thought of as mathematical curiosities, are now commonplace. The full promise of this marriage between two of our most advanced technologies is yet to be realized.





MODEL OF A VERTICAL / SHORT TAKEOFF OR LANDING (V/STOL) FIGHTER AIRCRAFT BEING PREPARED FOR TEST IN THE AMES 40 BY 80 FOOT WIND TUNNEL.





THE CONTOURS OF THE F-16 AIRCRAFT ARE MODELED BY CONNECTING POINTS ON THE SURFACE TO FORM A GRID. THE GRID DENSITY VARIES AT SPECIFIC LOCATIONS CONSISTENT WITH THE COMPLEXITY OF LOCALIZED FLOWS.

The NAS capability combines several necessary elements to produce an unparalleled scientific computing environment. The ingredients include: a supercomputer, various support processing systems, mass storage, graphics and display systems, and work stations linked with this nucleus via high speed data networks. The system is complete only when it includes the most important element of all, NAS users. The NAS capability is used by those pursuing advanced R&D in the aeronautical sciences and in other areas which require large scale computations.

The high speed processors that form the heart of the NAS system can be effective only when they can be efficiently accessed by local and remote users. The interactive systems that link users to processors provide a common operating communication system, reducing the complexities of computations to understandable outputs, creatively displayed.

The NAS Processing System Network (NPSN) is accessible to a nationwide community of remote users. This pacesetting capability provides state-of-the-art computing for United States aeronautics research and development.

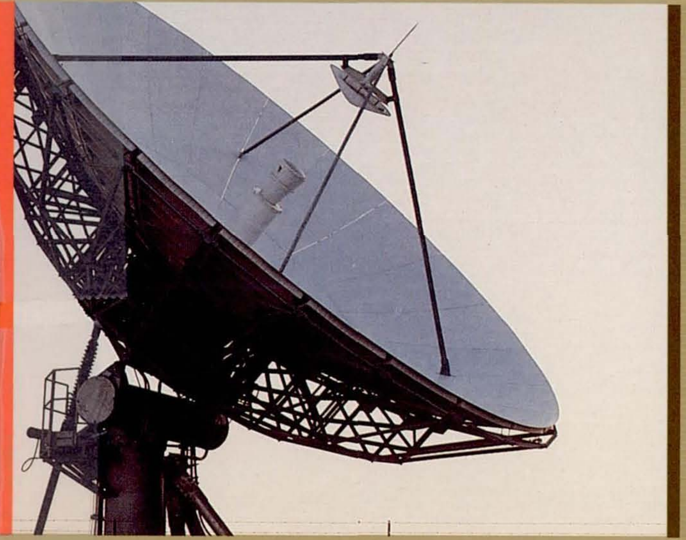
The NAS program has three goals:

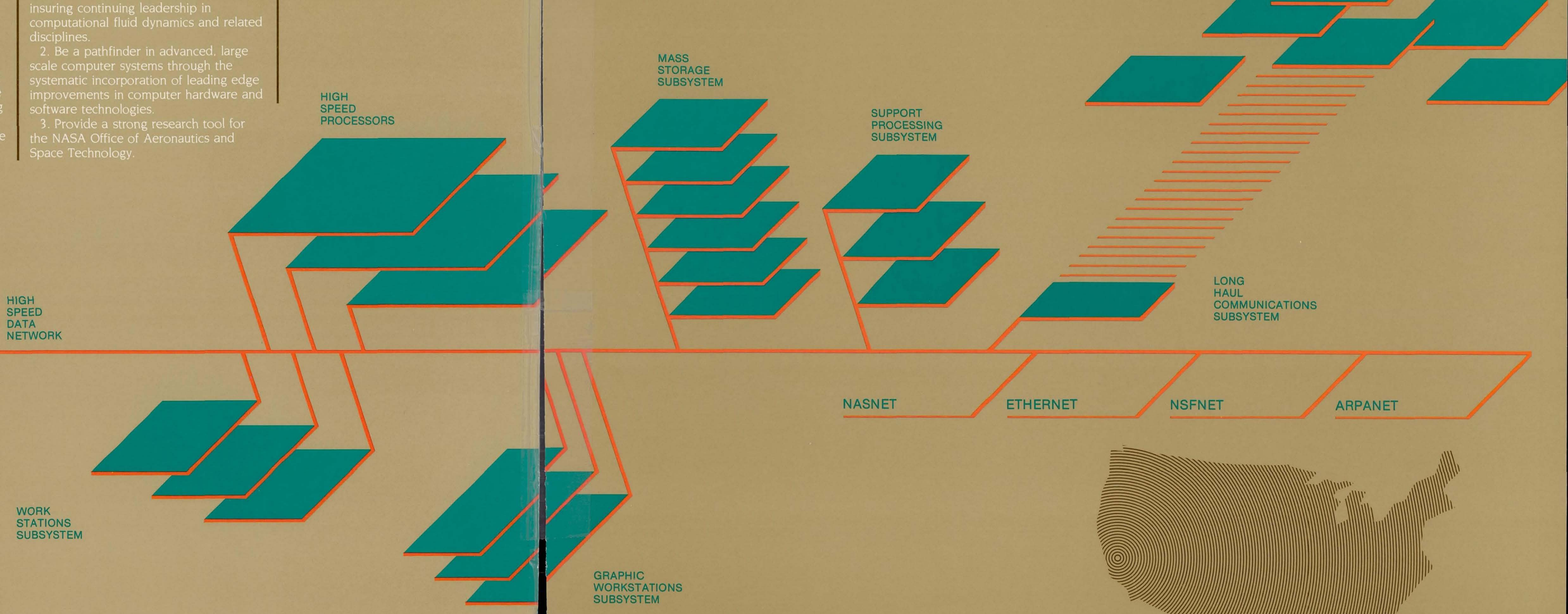
1. Establish a national computational capability, available to NASA, Department of Defense (DOD) and other government agencies, industry, and universities, as a necessary element in insuring continuing leadership in computational fluid dynamics and related disciplines.
2. Be a pathfinder in advanced, large scale computer systems through the systematic incorporation of leading edge improvements in computer hardware and software technologies.
3. Provide a strong research tool for the NASA Office of Aeronautics and Space Technology.

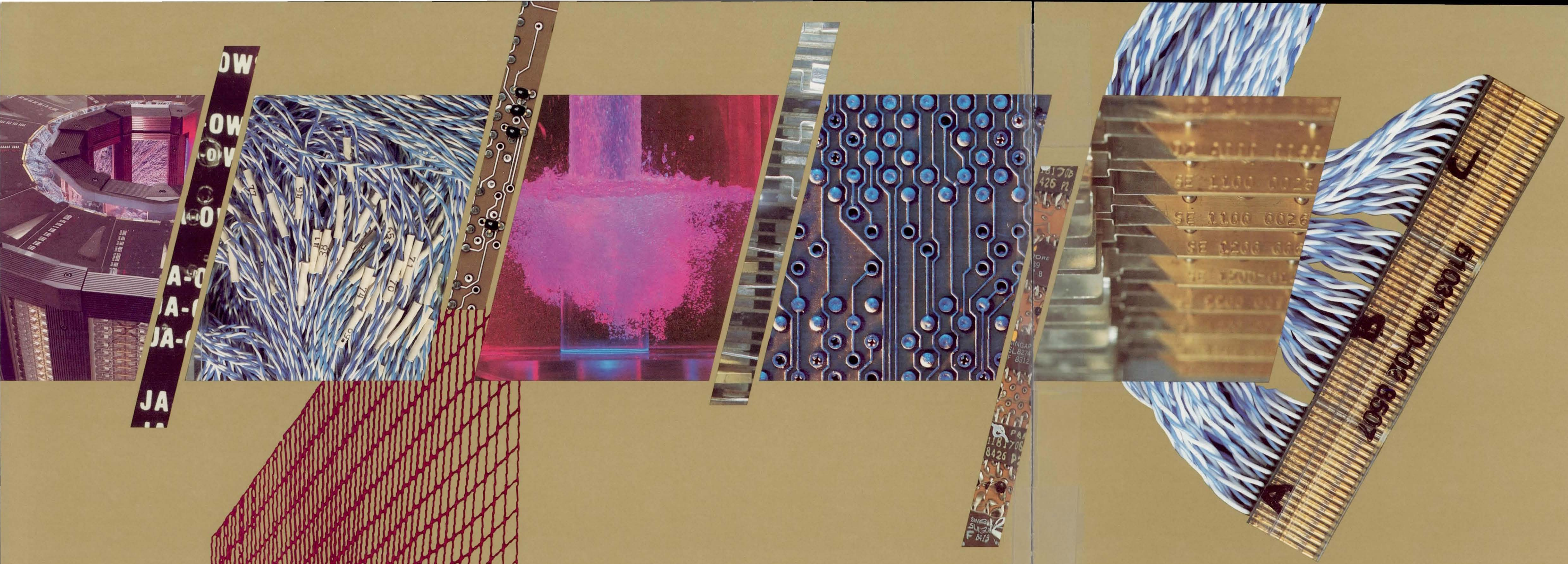
The initial operating phase began in the summer of 1986 and continues with the introduction of advanced systems and new facilities.

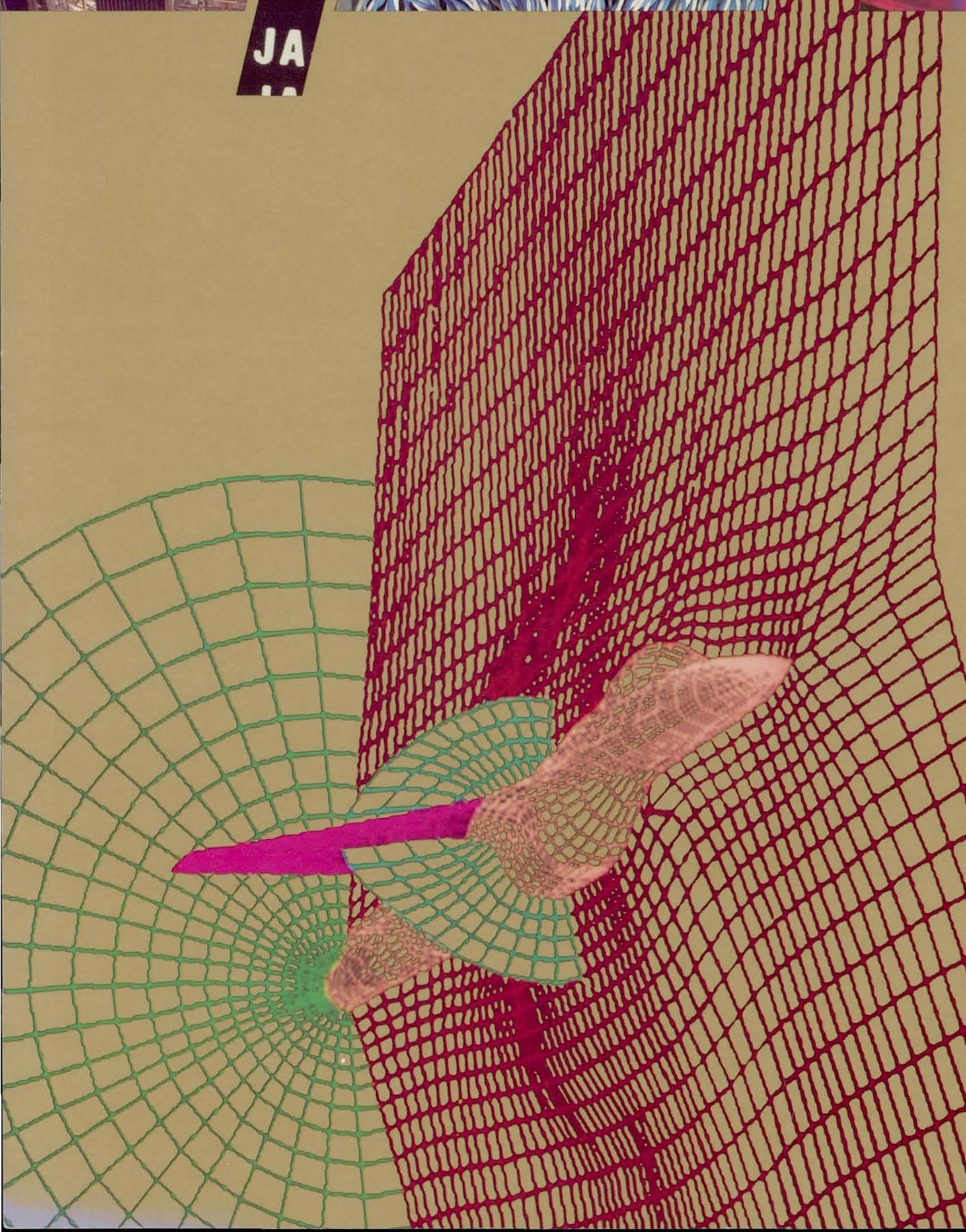
Implementation planning is evolutionary. The NAS strategy is to incorporate a sequence of successively more powerful prototype or early production model supercomputers as high speed processors. In this way, NAS will continue to meet the expanding needs and capabilities of its users.

System access is provided to users at geographically dispersed NASA centers, DOD and other government research installations, aerospace industry sites and universities. Effective use is made of existing communications networks such as ETHERNET, ARPANET and NSFNET. A broad range of communications bandwidths and services allow users access via terminals, work stations or other host computer systems.









The ongoing evolution of digital computers supports the progress of technology in many areas. Computers can be used to gain insight into physical phenomena too complicated to explore experimentally.

For over a century, the equations governing physical phenomena of fluid flow were understood, but we lacked the tools to obtain analytical solutions. Experimental observation was a means of solution, but many problems were too complex to allow investigation. Computers serve as a bridge to the future, providing a capability for studying the basic physics of turbulence, vortical flow, chemical and nuclear reactions, weather prediction, molecular modeling, and other engineering and scientific activities requiring large scale computations. Computational and experimental techniques can now be applied from complementary perspectives leading to an improved understanding of physical behavior.

This is a stimulating time for fluid dynamicists able to take advantage of the confluence of supercomputers, advances in applied mathematics and the improving science of fluid physics. Innovative computational architectures, coupled with the explosive growth in storage capacity and reductions in operating speeds, make it possible to observe complex, three dimensional flows at increasingly realistic scales and geometries. Astounding as the advances in computer technology have been, numerical aerodynamic simulation will continue to require increasingly more powerful computers to sustain the rate of progress in the astronautical sciences.

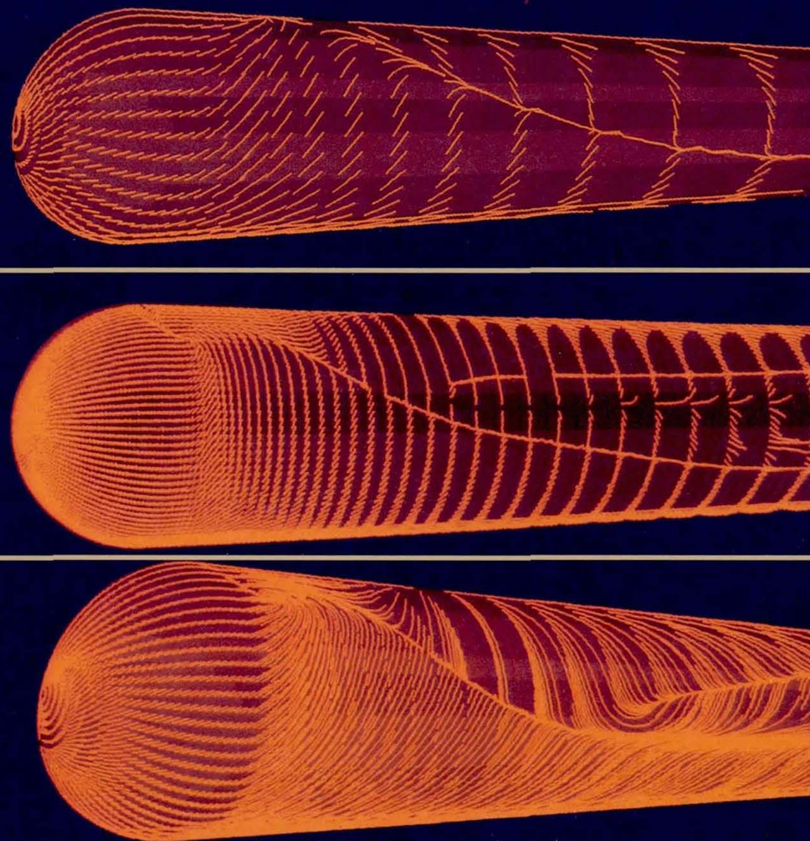
Computers are a part of contemporary life at many levels. Casual observers of this technology usually equate computational progress with speed. The speed of modern computers eclipse their predecessors every few years. At the same time, computers become smaller. However, the unrecognized leaders of computational design are storage capacity and problem specific architectures. Memory capacity has grown at an even faster rate than processing speed and powerful original architectures have arisen to match the problems that they are designated to solve.
It is difficult to project the conclusion of this counterpoint between applications and computing devices except to recognize that the unfolding scenario has just begun.

It is not the supercomputing machines that will make history, but the people using them. The salient characteristic of the computer age may be the general availability of a relatively rare localized resource.

This availability is in itself the result of another expanding technology, communications. Users are linked to the nucleus machine via high speed communication links that support interactive access for terminals, graphics work stations and other computers. Computers are playing an increasingly important role in all science and engineering disiplines.

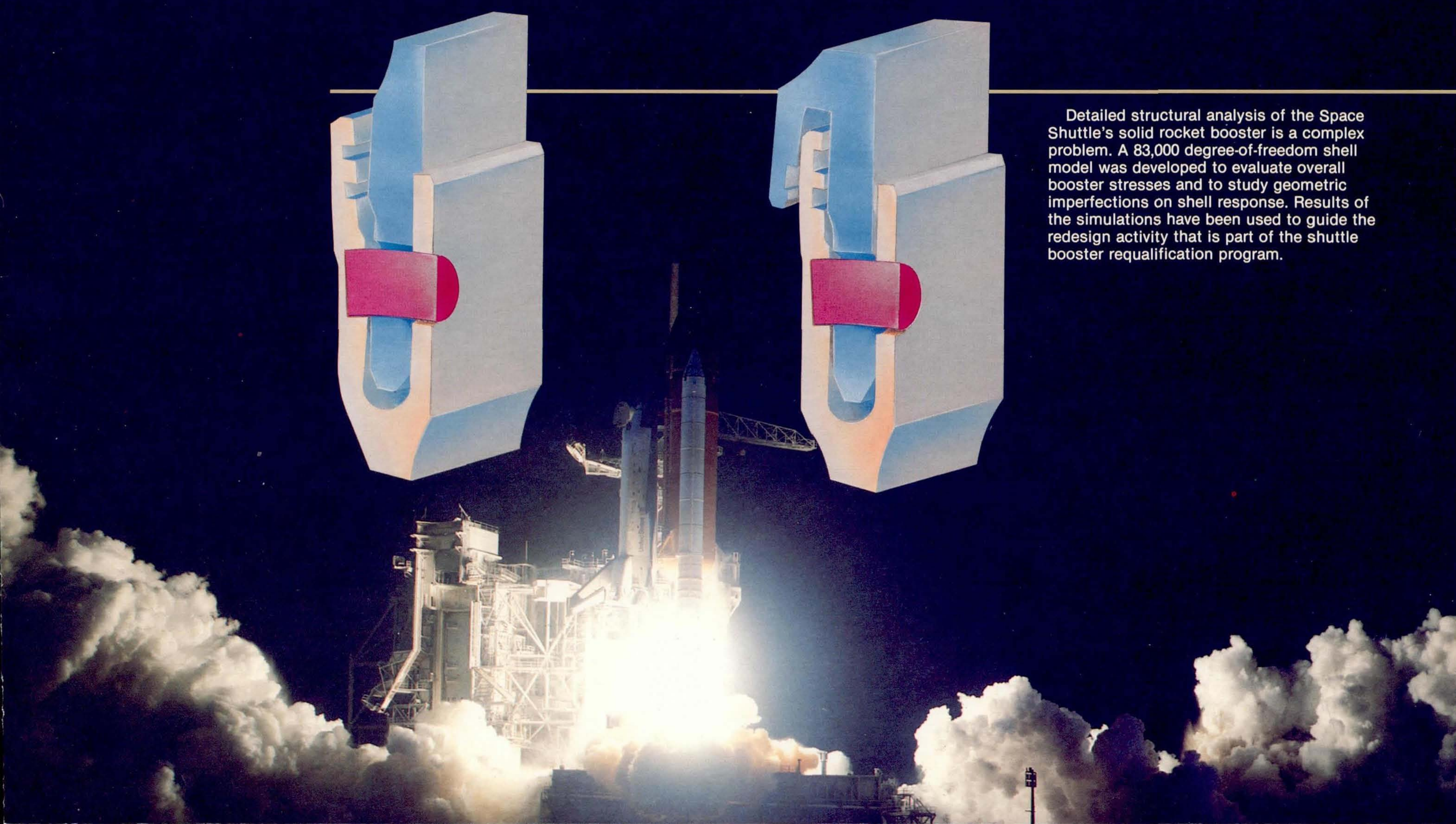
World leadership is indelibly linked to computer use in activities ranging from the day-to-day conduct of commerce to the heights of scientific discovery.

At the centerpoint of these endeavors are humans pursuing commercial and scientific goals. Their success is directly tied to the organic link that must exist between mind and machine. In the hands of an explorer, the computer can stimulate global transformation, economic and social revision, and scientific advancement.



Accuracy, fidelity, congruency; words that convey the ability to monitor and perceive the true characteristics of an event usually result from careful observations or simulations within relevant temporal, spectral and spatial scales. Improvements result from an ability to sample finer spatial grids on closely separated time steps. For example, the uppermost exhibit is consistent with three dimensional flow simulations associated with the grid density possible in 1978.

Observations became more refined as time progressed and the intricacies of flow were further revealed for even the simplest of structures. Finally, three dimensional simulations were achieved permitting new revelations about the flow around real world structures.



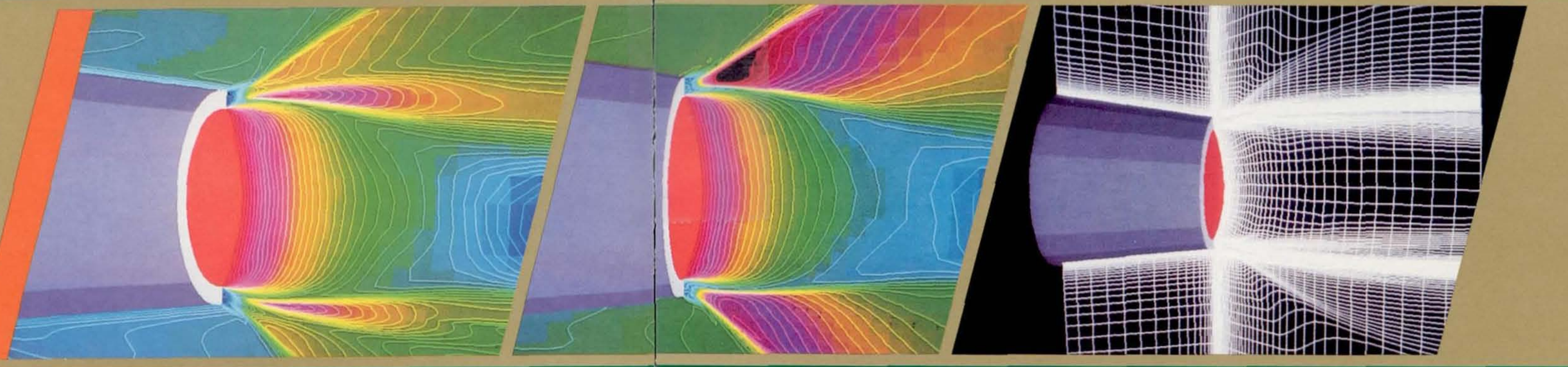
Detailed structural analysis of the Space Shuttle's solid rocket booster is a complex problem. A 83,000 degree-of-freedom shell model was developed to evaluate overall booster stresses and to study geometric imperfections on shell response. Results of the simulations have been used to guide the redesign activity that is part of the shuttle booster requalification program.

The NAS program is engaged in many pathfinding activities. Projects span a wide range of subjects in line with our national interests. Aeronautical subjects include commercial aircraft, modern fighter design, helicopter developments, improvements in Space Shuttle systems, and various subsystem and component developments. Research and development activities are focused on such diverse topics as chemical mixing and spacecraft attitude control. The proposed National Aerospace Plane is receiving considerable attention because of its operating environment that extends every element of contemporary analytical and experimental experience.

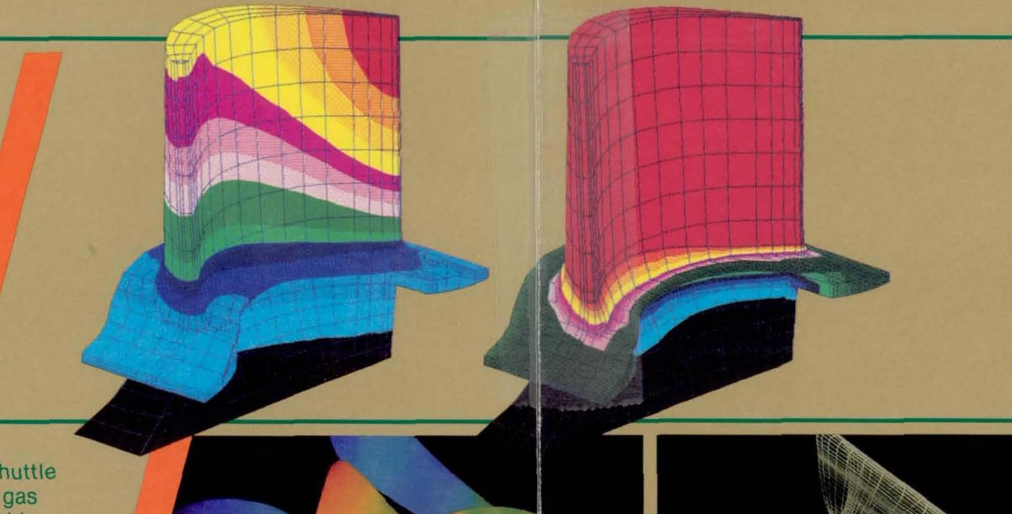
Pathfinding activities are crucial to the continued preeminence of our most important technologies. The long term economic and military security of the nation will hinge on how we use these tools to explore new paths while creating totally new technologies. Other nations are charting courses similar to ours with installations that bear a striking resemblance to the NAS facility.

Ultimately, success will be tied closely to the continued improvement of NAS, its availability to users anywhere in the United States and the establishment of a balanced set of priorities pertinent to the national interest.

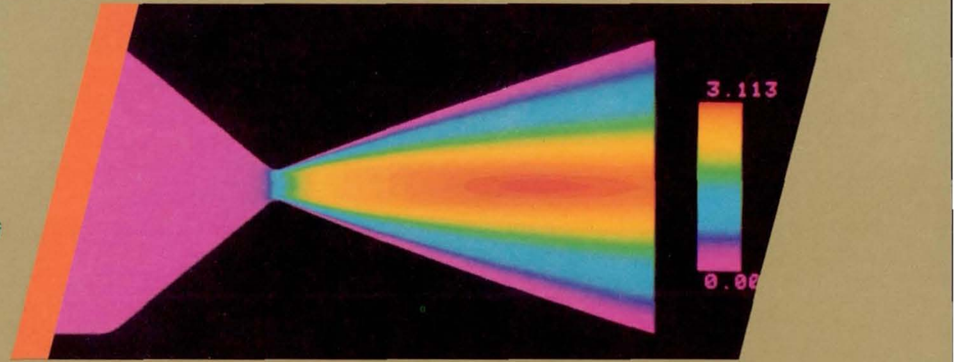
Three dimensional simulations improve understanding of the complex interactions between the jet exhaust and the surrounding flow field. A mach-2.5 jet flow is shown in a mach-2 flow field. Displayed in order are density and pressure traces with the solution adapted grid. Contours rapidly expand around the nozzle lip. Improvements in these flow field interactions will result in reduced drag and enhanced aircraft performance.



Turbine blades are subjected to severe thermomechanical loading with rotational speeds as high as 36,000 r.p.m. Non-linear, finite-element heat transfer analyses of the Space Shuttle main engine reveal thermomechanical performance levels at various points in the mission cycle.

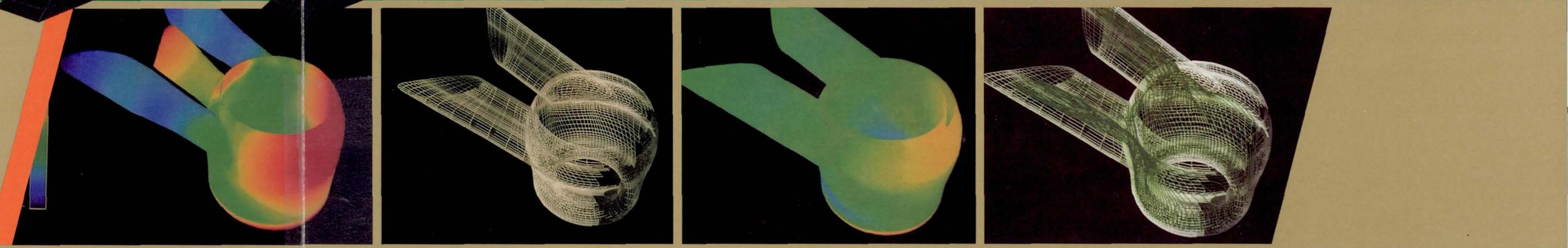


Computational results are being used to guide the design of the resistojet, which is a small low Reynolds number nozzle used for space-based attitude control. Two dimensional Navier-Stokes codes calculate mach number distributions, indicating that the boundary layer along the nozzle wall can grow faster than the nozzle expansion. This results in a highly non-uniform distribution with the maximum mach number occurring upstream of the nozzle exit.

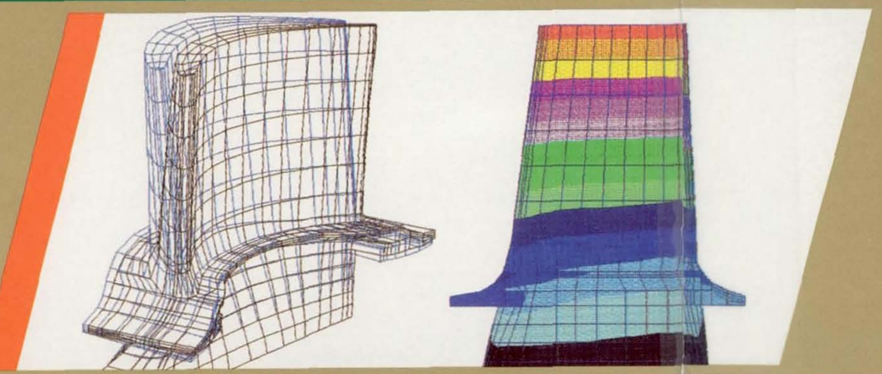


Surface panel analysis techniques are used to evaluate propeller aerodynamic interference for a next generation commercial aircraft design. High pressure, low velocity regions are shown in blue and low pressure, high velocity flow in red. The velocity field for the wing section depicts freestream velocities with blue representing subsonic stagnation, yellow sonic velocities and red supersonic velocities.

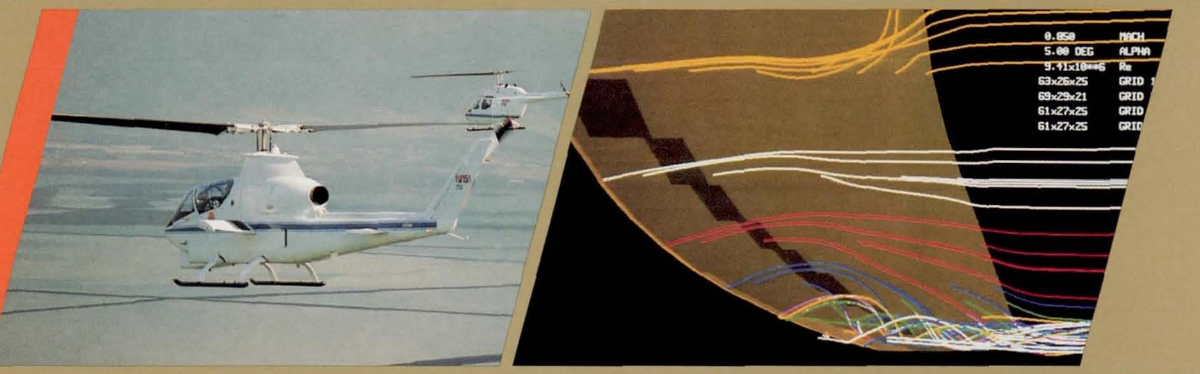
Computers were used to analyze the complex flow phenomena in the Space Shuttle main engine and lead to an improved hot gas manifold design. The current three manifold tube design has considerable pressure variability. The new two tube design provides a more even pressure distribution, which is also confirmed by the particle flow analysis.



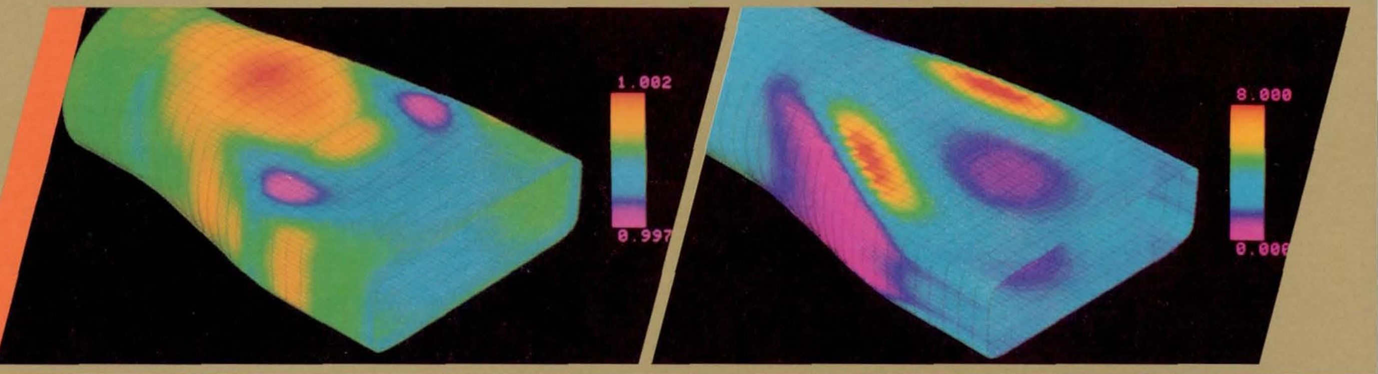
Turbine blade material characteristics become nonlinear in critical locations during normal operation. Structural blade performance is assessed numerically in terms of deformation, stresses and vibratory natural frequencies. Constant displacement contours of the pressure surface are shown for a modal frequency of 4487 Hz.



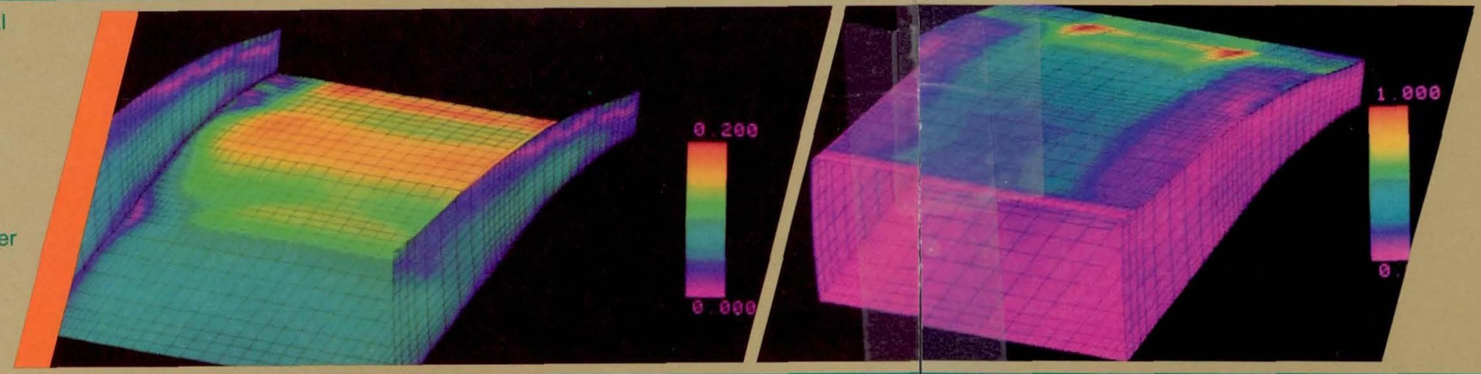
Numerical simulation technologies are used in helicopter rotor blade designs. Particles released at the tip of a wing form a vortex, then braid and roll up as they lift off the surface. The far field view of the tip vortex in the second image shows vorticity levels decreasing downstream.



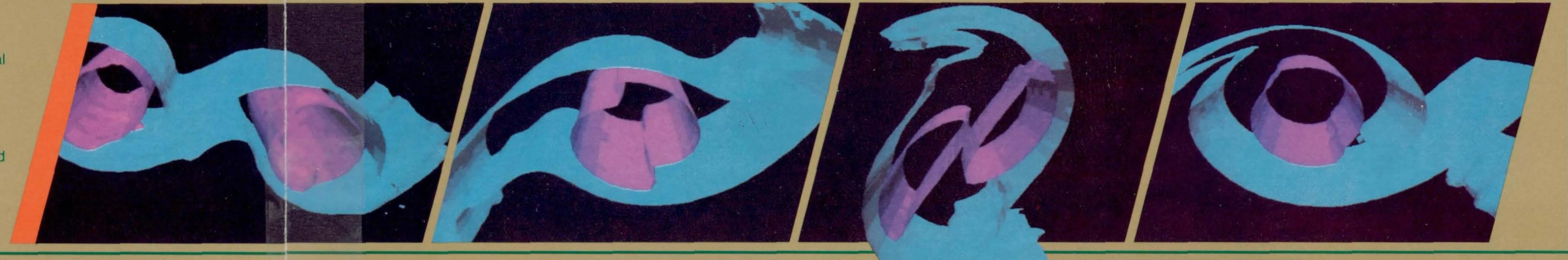
Highly maneuverable, supersonic aircraft depend on engine exhaust ducts and nozzles to provide the required thrust vectoring capability. Researchers are using three dimensional, Parabolized Navier-Stokes (PNS) codes to predict aerodynamic and heat transfer characteristics. The figures show surface plots of calculated static pressure and skin friction for the round-to-rectangular transition section of a benchmark nozzle.



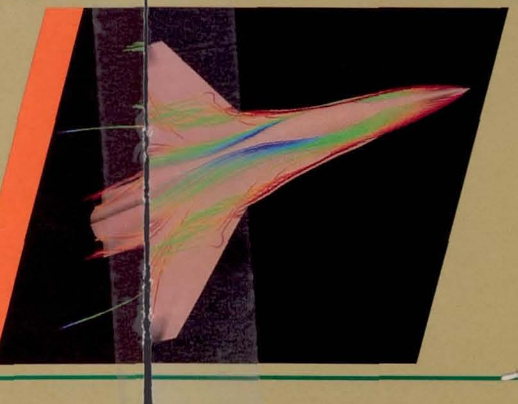
The hypersonic environment of the National Aerospace Plane places special emphasis on inlet performance. Numerical techniques are being used to study the effects of shock boundary layer interactions on hypersonic mixed compression inlets. Surface plots demonstrate the calculated skin friction on a cowl and ramp of a mach-5 inlet. Numerical results will be compared with data from benchmark experiments to verify the computer code.



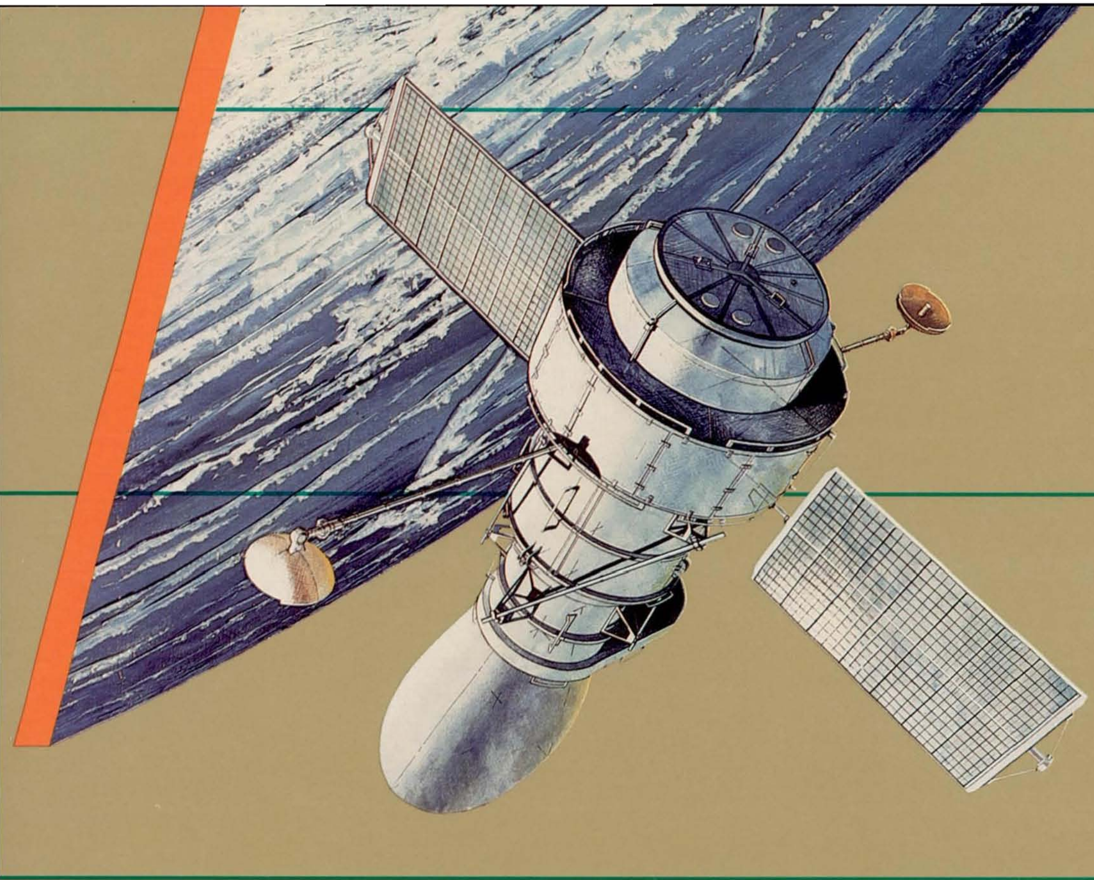
Turbulent mixing can have a strong effect on chemical reactions, but the small scale of streamwise vortex structures make detailed experimental investigations difficult. Numerical simulations provide a "microscope" with which to follow the evolution of vortex structures as they flow downstream. Three-dimensional surface plots, at 9-second intervals, were produced from a simulation of developing shear layers subjected to combined harmonic and subharmonic acoustic noise.



Developments of modern fighter aircraft rely on computational analysis. This flow field illustrates particle height above a simplified model of the F-16A fuselage and wing assembly. While red traces hug the body, blue and yellow streams show the increasing height of particle flow. This technique permits the identification and improvement of separated flow regions which might lead to stall and dynamic instability.

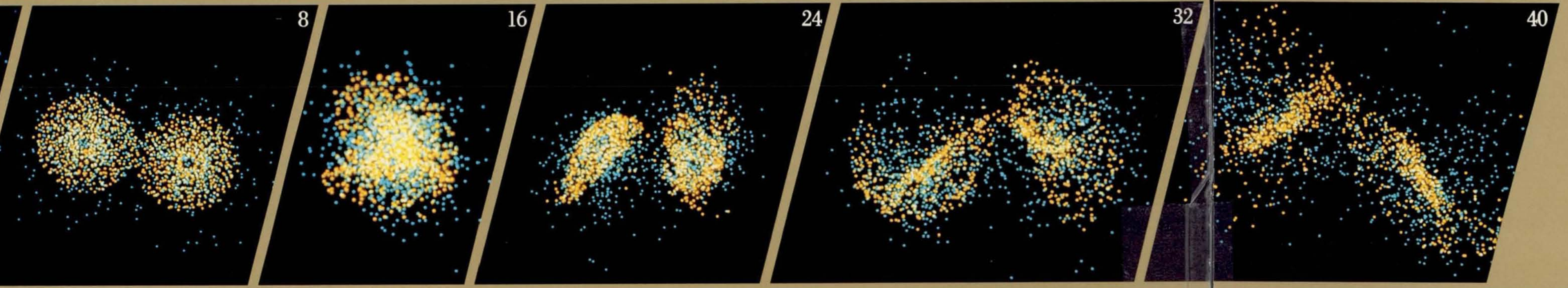


Surface pressure on the AV-8B Harrier Forebody-Inlet is shown with a proposed sensor pod installed on the upper forebody. The modeled condition is mach-0.67 at a zero degree angle of attack, with the cruise mass flow rate passing through each inlet. Engineers have used this and other solutions to assess the affect of various pod geometries and installation locations on inlet performance.

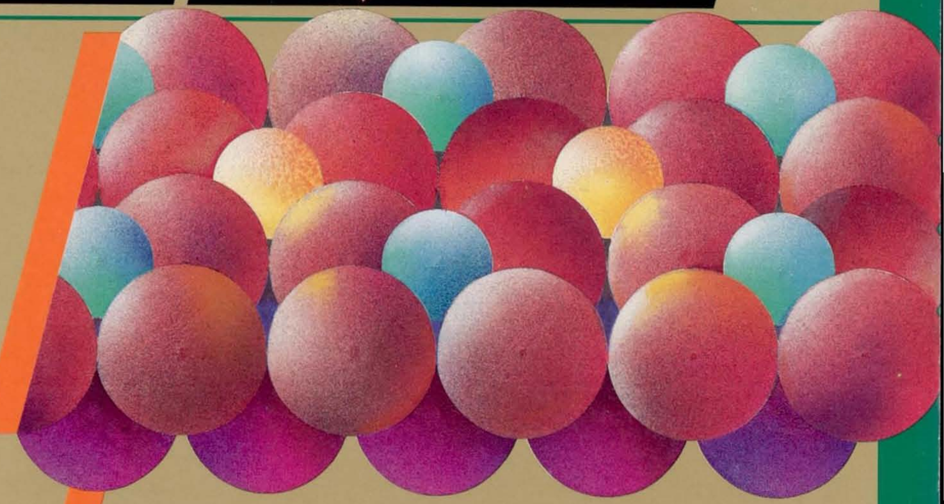


Dramatic improvements in flow field detail are made possible by increases in grid density. The first three figures are pressure contour plots in crossflow planes over a Strake-Delta wing. The low pressure vortex core is yellow or green and the free stream corresponds to the reddish color. The first figure shows the computed result using about 30,000 grid points, followed by 120,000 and 800,000 grid point solutions which parallel computational improvements over a decade. The fine grid vortex core is much larger near the wing trailing edge as compared to the coarse grid results. This indicates the correct prediction of vortex breakdown in the fine grid results, but not in the coarse grid results. Yellow particles reveal flow reversal, associated with vortex breakdown, only in the dense grid plot.

Numerical experiments will provide crucial insights into the nature of galactic evolution. Future space telescopes will provide observational evidence of numerically generated theoretical predictions. Cosmic events, such as colliding galaxies, which span billions of years, are condensed into seconds by the computer.

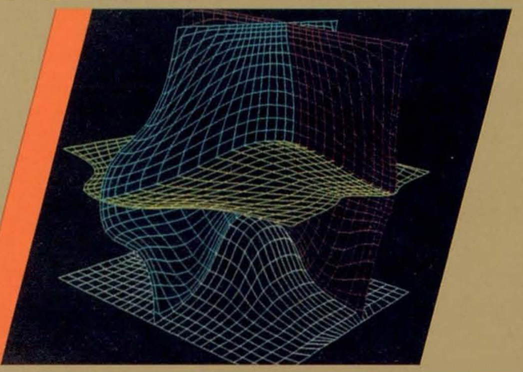


Operations in space show that ambient atomic oxygen presents a troublesome environment for organic, graphite and metallic surfaces, causing structural degradation and changes in thermal characteristics, reflectivity and conductivity. These changes are caused by high energy impact and chemical reactivity due to absorption of gaseous atoms on the material surfaces. Computational chemistry is probing the kinetics and mechanisms associated with these phenomena to develop more stable and resistant materials.

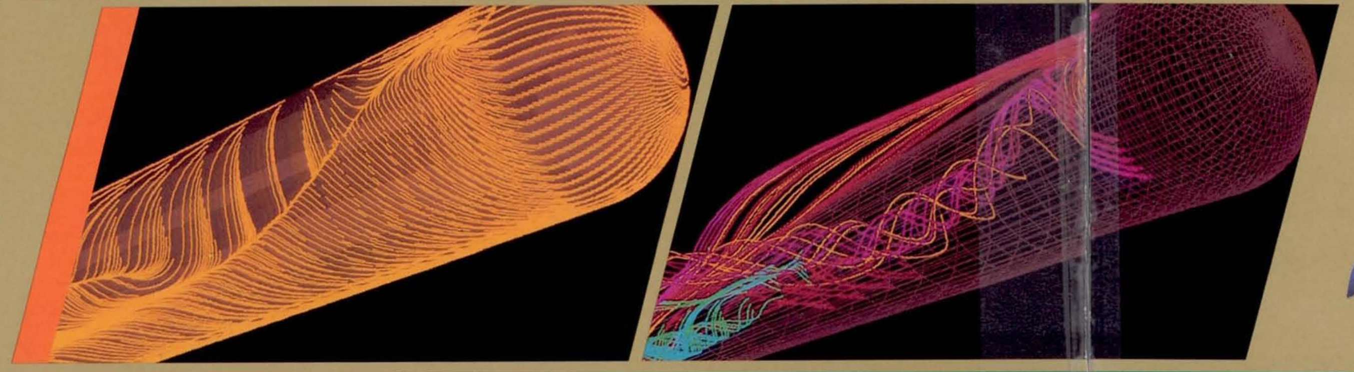


If the success of pathfinding projects governs our technological well being over the short term, the selection and pursuit of futuristic themes will determine our destiny.

Special evaluation tools are being produced to support future numerical analyses. The three dimensional grid generator is capable of providing block grids with control of cell size and skewness at all six faces of a computational cube. Computational cubes can be warped to fit around, inside, over, under and through any fluid dynamic configuration. This method can be used to combine any number of blocks with various boundary treatments.



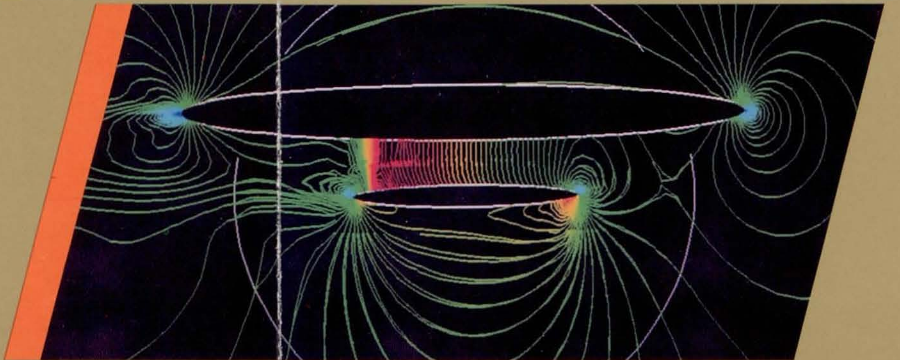
When an aircraft is maneuvering at large angles of attack, extensive regions of separated flow occur. Until very recently, our knowledge base was limited to experimental measurements. The NAS system extends our capability into three dimensional separated flows with realistic grid resolutions. These surface and off-surface particle traces were computed for a hemisphere-cylinder at a large angle of attack.



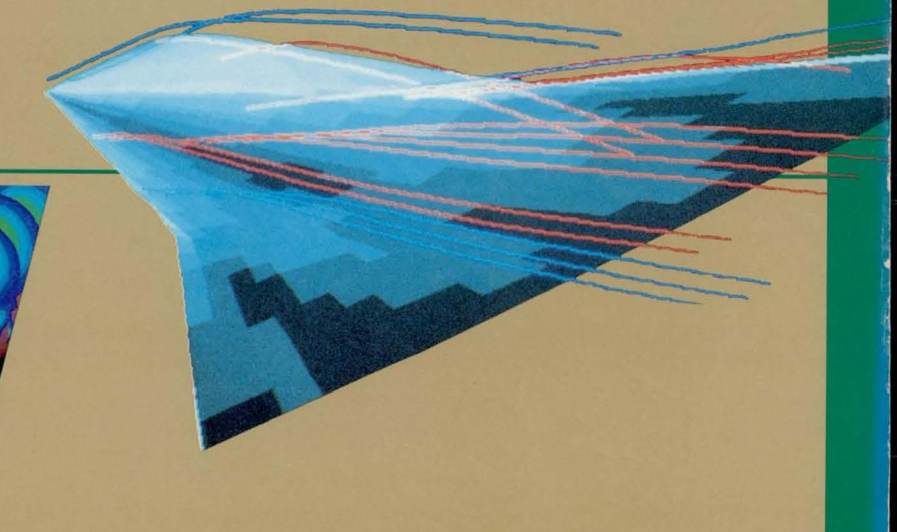
Advanced aircraft design has become heavily dependent on computational structural mechanics. The experimental X-29 aircraft required the development of new codes capable of evaluating the stresses associated with the unconventional forward swept wing design. Tomorrow's vanguard designs will be incubated in the computer.

Projections of this nature require an intuitive understanding blended with the cognitive skills necessary to investigate the unknown.

The release of weapons from high speed aircraft can be a dangerous operation. Reverse flow and other uncertainties in the turbulent field are difficult to evaluate experimentally. Numerical methods are being used successfully to evaluate these complex interactions. This image demonstrates the pressure field surrounding both the aircraft wing and the just-separated body.

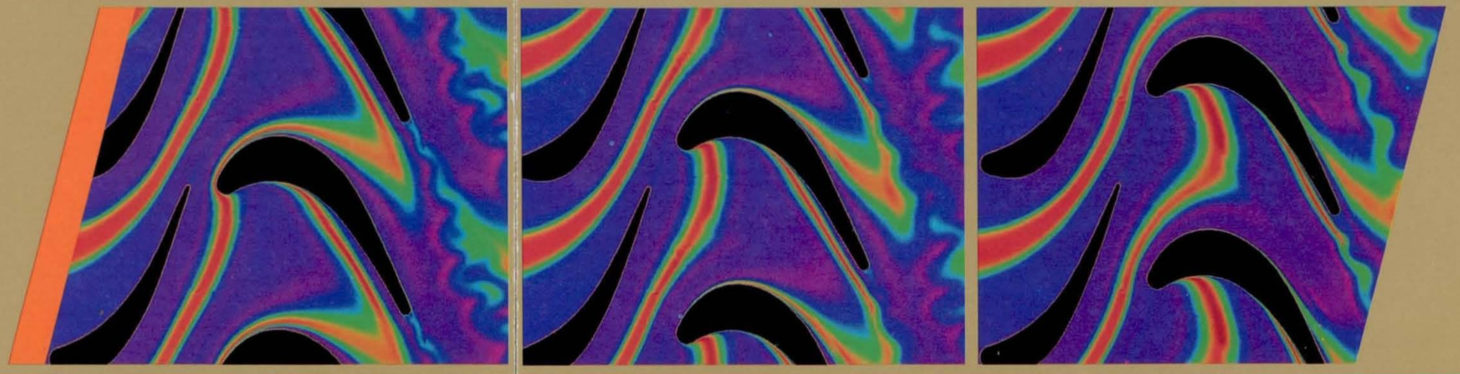


The bursting vortex process is a sequence of events occurring in the wall region of turbulent flows. These processes are responsible for most of the turbulence. The computations show the "horseshoe" vortex structures associated with the bursting process. Computational investigations of detailed velocity fields led to the discovery of several new organized turbulence structures. It was also possible to resolve an existing controversy by demonstrating that two different structures coexist in the flow field.

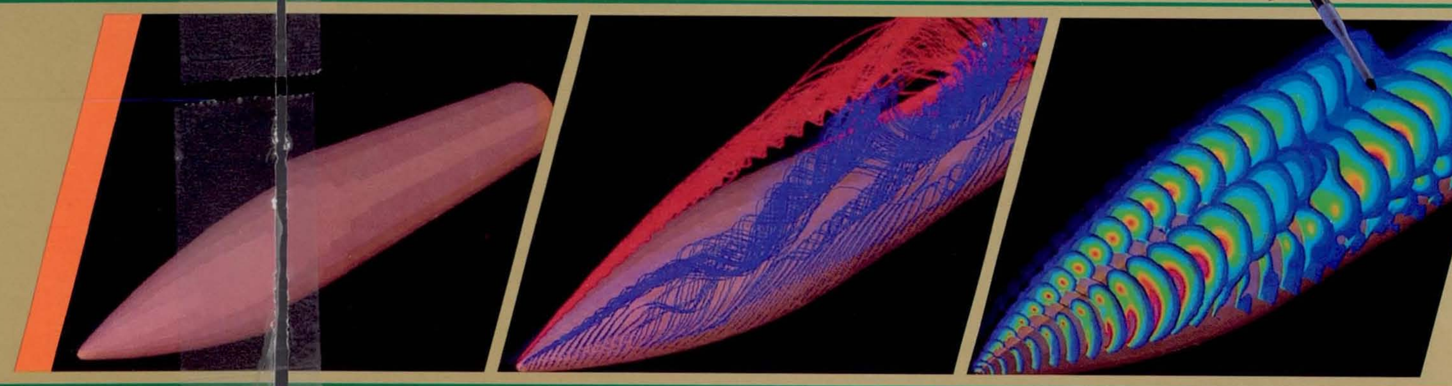


The subjects selected for future analysis consist of the development of new techniques for examining fluid flow, chemical reactions and other fundamental touchstones that rule the natural order and behavior of our world and universe.

The phenomena of hot streaks encountered in turbines have prompted numerical evaluation of combustor exit gas temperature inhomogeneities. Analyses show temperature variations as the rotor moves relative to the stator. The interaction of the hot gases is calculated and graphically animated. The inherent uneven distribution of temperatures indicates cooling systems cannot be based on average temperature performance.



The side forces and moments associated with vortex asymmetry can lead to uncontrolled flight conditions for aircraft and missiles maneuvering at large angles of attack. At least four major vortices appear as density contours shedding asymmetrically from an ogive body characterizing a modern aircraft fuselage. The same 40 degree angle of attack was used to generate particle traces, which confirm the multiple vortices.



The prediction of future accomplishments made possible by the computer is a challenge.

The pattern of exponential growth in computational capabilities is expected to continue for some time as a result of large scale electronics integration, storage capacity and computer architecture technologies.

Advancements in computer performance have been closely paralleled by improvements in numerical algorithms.

The results of this partnership have provided five orders of magnitude decrease in the cost of performing a computation in the last fifteen years.

Theory and experimentation are entwined in a reinforcing way. In some cases, the physical observation comes first, in others the situation is reversed.

The relative roles of theory and experiment have reached a new plateau with the introduction of the digital computer.

In the past, computers represented a new tool for the scientist and engineer. They are now indispensible.

Together, the computational and experimental disciplines will yield a more complete understanding of physical phenomena leading to rapid advances in many areas of human endeavor.

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LEWIS RESEARCH CENTER

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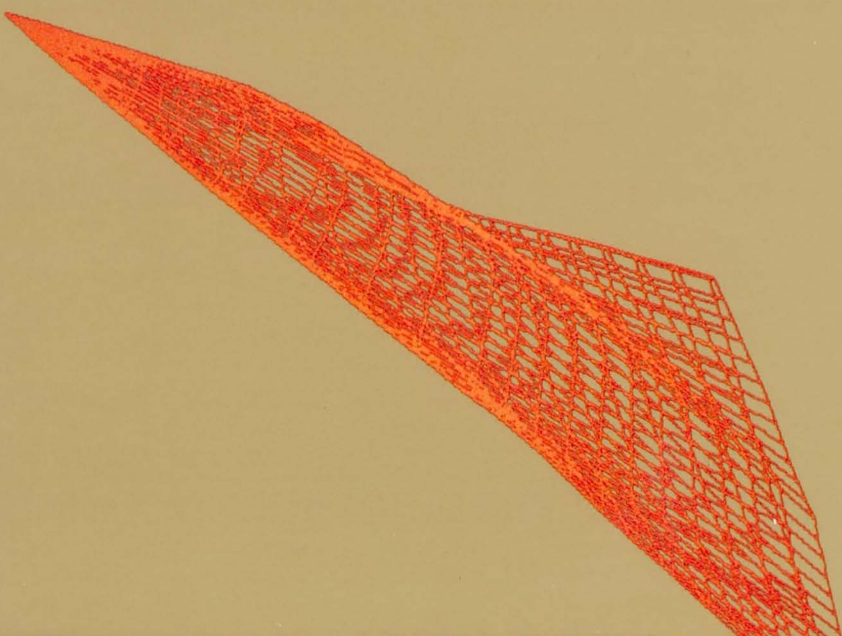
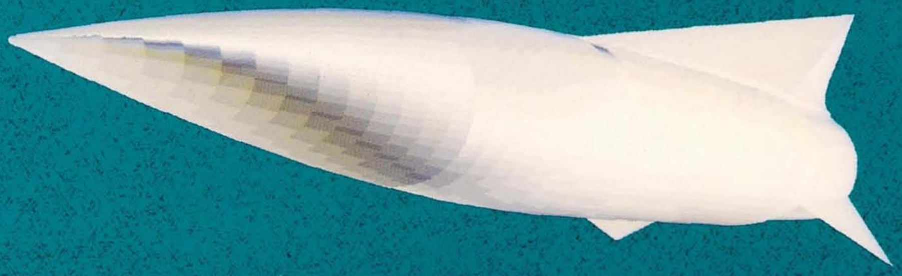
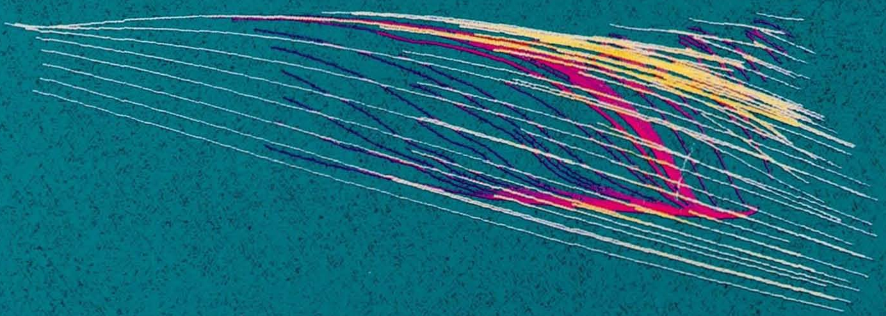
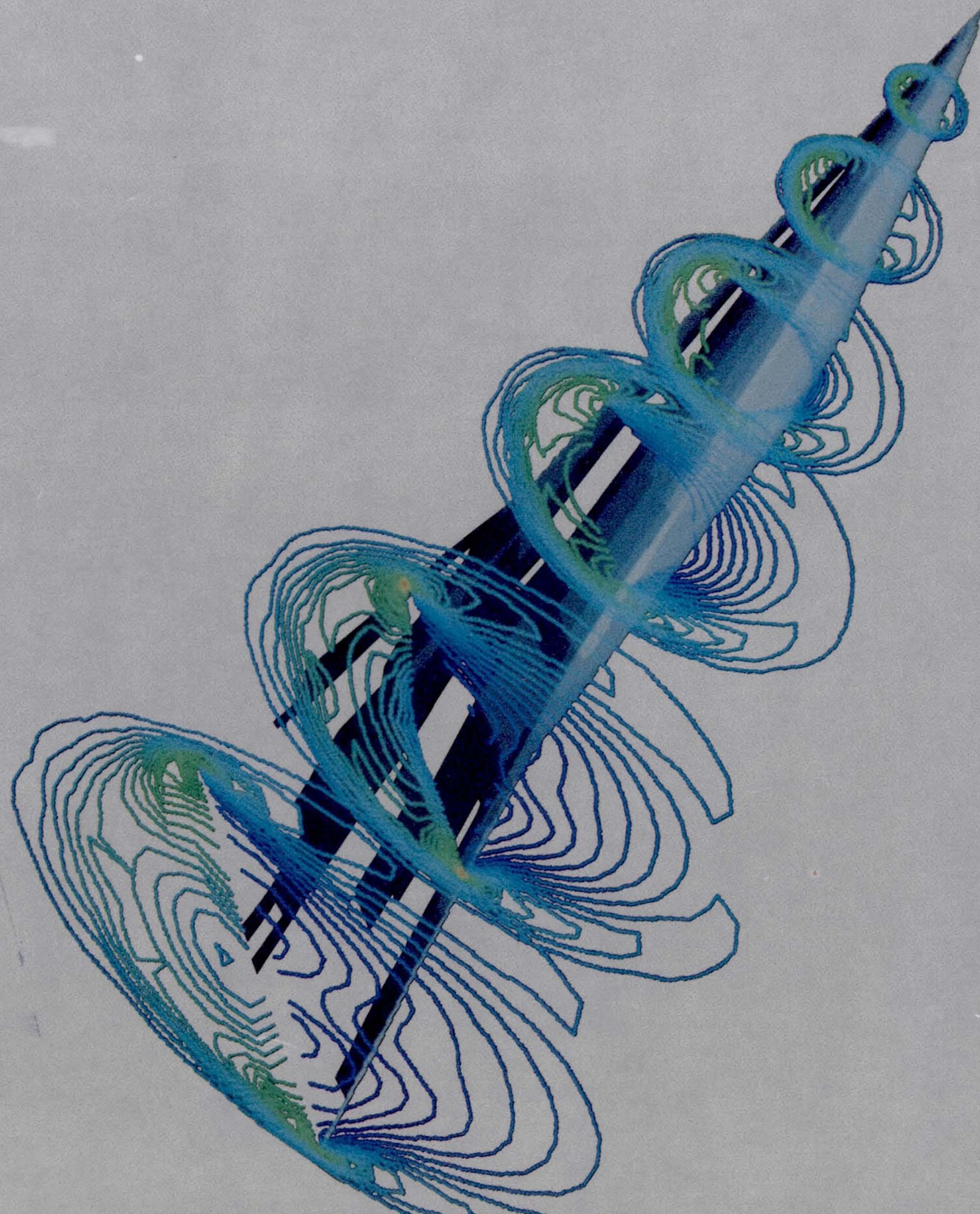


Numerical aerodynamic simulation often enters the domain of art. These particle flows provide the viewer with dashes of color as if from the brushstroke of an artist.





Shown are particle traces of a candidate configuration of the future national aerospace plane. Subsonic, supersonic and hypersonic flow fields about complex vehicles with wings, tails, fins, etc., can be accurately predicted and shown in a very physical manner.



National Aeronautics and
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