



Influence of Computational Fluid Dynamics on Experimental Aerospace Facilities: A Fifteen Year Projection (1983)

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**Influence of Computational Fluid Dynamics on Experimental
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An assessment was made of the impact of developments in computational fluid dynamics (CFD) on the traditional role of aerospace ground test facilities over the next fifteen years. With improvements in CFD and more powerful scientific computers projected over this period it is expected to have the capability to compute the flow over a complete aircraft at a unit cost three orders of magnitude lower than presently possible. Over the same period improvements in ground test facilities will progress by application of computational techniques including CFD to data acquisition, facility operational efficiency, and simulation of the flight envelope; however, no dramatic change in unit cost is expected as greater efficiency will be countered by higher energy and labor costs. Strengths and weaknesses of wind tunnel testing and CFD for aircraft and engine design are discussed. Although CFD is increasingly becoming a powerful tool, its extensive application to airframe and engine design hinges on the confidence that the designers and management have in its ability to provide design data of comparative value to that of test facilities. For the next fifteen years it is expected that CFD and ground test facilities will be used in a complementary mode with no appreciable reductions in testing.

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↑ **The Influence of Computational Fluid Dynamics on Experimental Aerospace Facilities**

A Fifteen Year Projection

Prepared by the ^{*4}Committee on
1 Computational Aerodynamics Simulation Technology Developments
3 Aeronautics and Space Engineering Board
2 Commission on Engineering and Technical Systems
1 National Research Council

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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Summary

In response to a joint request from the Arnold Engineering Development Center of the Air Force Systems Command and the Office of Aeronautics and Space Technology of the National Aeronautics and Space Administration, an ad hoc committee of the National Research Council's Aeronautics and Space Engineering Board conducted an assessment of the impact of developments in computational fluid dynamics (CFD) on the traditional role of conventional aeronautical ground test facilities over the next 15 years (Memorandum of Understanding, Appendix A).

RAPID PROGRESS IN CFD TECHNIQUES

There are four main stages in computational fluid dynamics, each representing the employment of a successively refined approximation of the full Navier-Stokes equations that govern fluid motion:

<u>Stage</u>	<u>Approximation</u>
I	Linearized inviscid
Ia	Linearized inviscid plus boundary layer
II	Nonlinear inviscid (Euler)
IIa	Nonlinear inviscid plus interacting boundary layer
III	Reynolds-averaged Navier-Stokes
IV	Full Navier-Stokes (large eddy simulations with small scale turbulence modeling)

Stages I and II are already in limited use, and Stage III is expected to be universally used within the next 15 years. The principal items pacing introduction of Stage III into the aerodynamic design process are: (1) development of improved turbulence models; (2) development of more powerful scientific computers; and (3) development of more efficient numerical algorithms.

With regard to advances in supercomputers in the next 15 years the committee projects an increase in speed up to 10^4 millions of floating point operations per second (MFLOPS) with memory size of approximately 500 megawords through use of 1 megabit memory chips.¹ Advances in these three areas are expected to result in the ability to practically compute the flow field about a complete aircraft with the Reynolds-averaged Navier-Stokes equations (Stage III). Uncertainties arising from transition and turbulence modeling are viewed as the primary limitation of CFD within Stage III.

CONSIDERATIONS IN DESIGN: TEST FACILITIES AND CFD

To acquire confidence in the aerodynamic design of a typical major aerospace project, the developer currently invests for experimental verification about 2 percent of the non-recurring development costs of major aircraft programs. This total cost--typically \$1 B to \$2 B--is so large as to put the entire current resources and future reputation of the company at risk. The designer's primary objective is to reduce this risk at the earliest possible phase of the development, and he will not change from tried and proven verification methods until equal confidence in new techniques has been built up.

CFD, as a new technique for obtaining aerodynamic design information, will therefore be assessed in accordance with the four questions which follow, in order of priority.

(1) Does CFD increase confidence in the design?

For the entire period of 15 years covered in this study, CFD analysis and traditional experimental methods will usually have somewhat different roles which are complementary to each other. Agreement between the two techniques will build confidence in CFD and will also strengthen the company's confidence in the new design.

(2) Will CFD result in more complete information?

Computational methods can provide more detailed information on the aerodynamic flow field than the most heavily instrumented wind tunnel model. The usefulness of this information is dependent on the validity of the physical model used.

¹Projections of future supercomputer capability should take into account the signs of a slowdown in the further development of large computers in the United States. With active development of supercomputers by Japanese industry strongly supported by its government, the broader implication is loss of U.S. leadership.

- (3) Will CFD result in earlier acquisition of design data?
- (4) Will CFD reduce the cost of obtaining design data?

The prototype development will be geared to the test facility schedule, as in the past, until the designer gains sufficient confidence in CFD calculations to act upon them without waiting for experimental verification. This point is several years away, but when it is reached, the cost savings associated with earlier design data acquisition are likely to be far greater than the saving in cost of data acquisition itself. However, the roles of each method would be based on its relative strengths and weaknesses as time progresses.

Cost Considerations

During the period under consideration, the cost effectiveness of scientific computers is expected to improve by a factor of 30. A comparable improvement by a factor of 30 expected in efficiency of numerical techniques will enable computation of realistic flow fields and reduce cost by a factor of 1000, which makes large scale computation affordable (Chapter II). A lesser change in the unit cost of test facility operations is expected, partly from the advances in computer technology (Appendix D). However, since ground test facilities and CFD are seen as complementary during the next 15 years, direct cost comparisons are not regarded as meaningful.

USER VIEWPOINT

An extensive survey is given of the tests most commonly required in development of aircraft and engines and assessments are made of the relative strengths and weaknesses of ground facility testing and CFD at the present time and projected 15 years hence. This information makes it clear that wind tunnel testing and CFD are complementary in the design and analysis of aircraft, and their roles will change as the techniques evolve.

CFD provides detailed insight of a flow locally, geometrical "design" information, and allows rapid analysis iteration of configuration modifications.

Wind tunnel testing provides a global integration of the flow field, more developed and more useful flow visualization techniques, and an efficient means of collecting "data base" information once a final configuration model is built.

When an aerodynamic effect of significance is encountered, it is frequently studied by both techniques.

THE GAP BETWEEN CFD RESEARCH AND USAGE

Between the CFD research phase and the establishment of a mature design capability, there is an essential development phase in which

CFD techniques and algorithms are converted to user-oriented methods applicable to the design process. NASA supports CFD research; CFD development is seen as an appropriate area for support by federal user agencies.

TEST FACILITY ENHANCEMENT BY CFD

As noted above, an extensive period of complementary use of CFD and test facilities for verification is needed. However, during the next 15 years, the type of testing may change, but the amount of testing will not appreciably diminish. During this period, data quality, facility operational efficiency, and simulation of the flight environment can be improved by application of a number of computational techniques, including CFD applications.

NEW TEST FACILITY REQUIREMENTS

For the next fifteen years those aerodynamic test facilities which are primarily engaged in development tests for new aircraft and engines will have a second major function: verification of CFD applications to design. These functions have been examined using committee members' own projections of probable new programs, and recognizing the important part to be played by the new facilities of NASA and AEDC, viz National Transonic Facility (NTF), Aeropropulsion System Test Facility (ASTF), and Ames 80'x120' Wind Tunnel. It appears that, with the possible exception of test requirements of Vertical and Short Takeoff and Landing (V/STOL) aircraft, the facilities will be adequate for the task.

It is probable that the hypersonic reentry vehicle, which already depends more than any other flow regime on design by analytical methods, will arrive at full CFD application and confidence at an early stage, while full utilization of CFD techniques for high performance aircraft design and engine testing will occur at a much later date.

CONCLUSION

CFD is already a powerful tool and its strength will increase significantly in the next five to ten years to the point where it can be a very important aircraft and engine design tool; however, the extensive application of CFD hinges upon two major considerations. First, the designer must have a high degree of confidence in the computational methods for aerodynamic design as compared to testing. Second, management from industry and government must have confidence that CFD is a more efficient developmental tool than extensive wind tunnel testing. For the next 15 years, CFD and ground test facilities will be used in a complementary mode with no appreciable reductions in testing anticipated.

I

Introduction

Significant advances in computational fluid dynamics (CFD) as a result of improvements in numerical algorithms as well as in processing speed and storage capacity of new generations of computers make CFD an ever more powerful tool in the aerodynamic design of aerospace systems.

The present study's purpose is to assess broadly the impact of developments in computational fluid dynamics on the traditional role of conventional aeronautical ground test facilities over the next 15 years.

The study was requested and supported jointly by the Air Force Systems Command's (AFSC) Arnold Engineering Development Center (AEDC) and NASA's Office of Aeronautics and Space Technology (OAST), and was undertaken by an ad hoc committee of the National Research Council's Aeronautics and Space Engineering Board. The Memorandum of Understanding between AFSC and NASA regarding the study appears in Appendix A.

The task called for many areas of expertise and the committee's membership included airframe and aircraft engine designers, computer and wind tunnel technologists, computational fluid dynamicists, and specialists in turbulence and boundary layer transition modeling.

The specific charges to the committee were to:

o Examine predicted changes in computer storage and processing capabilities and associated cost trends applicable to internal and external aerodynamic flow simulations during the next 15 years. In its deliberations the committee considered current aeronautical literature and generated original background documentation. This subject is treated in Chapter II and background information regarding the Status and Prospects for Improved Numerical Methods and the Outlook for Supercomputer Development appear in Appendixes B and C. Other sources are listed in the Bibliography.

o Interpret such trend data in terms of approximate cost to solve design and development problems and then compare them with the anticipated cost of using ground development facilities to obtain similar results. This area is considered in Chapter III. While the committee concluded direct cost comparisons are not meaningful, for the sake of completeness, cost data have been included in Appendix D.

o Identify classes of design problems that are better handled either by computational fluid dynamics or by ground development facilities. This evaluation was conducted by the users of such information and their views are given in Chapter IV.

o Identify, in particular, types of problems that are not likely to be handled adequately by computational fluid dynamics and for which a satisfactory ground development capability does not exist. This information appears in Chapter V.

o Review the long-range plans of the AEDC in light of the trends and problems identified by the committee and emphasizing the types of ground development facilities used at the Center. This review has been submitted to the AEDC in a separate document.

In developing this report, the committee held three two-day meetings as follows: February 9-10, 1982, at the U.S. Air Force Arnold Engineering Development Center, Tullahoma, Tennessee; May 25-26, 1982, at the NASA Ames Research Center, Moffett Field, California; and October 12-13, 1982, at the NASA Lewis Research Center, Cleveland, Ohio.

Members of the committee wish to acknowledge the valuable assistance of observers listed on pages iii and iv.

II

Current and Projected Capabilities of Computational Fluid Dynamics at the R&D Level

II-1. STAGES OF DEVELOPMENT

The historical progress in computational fluid dynamics can be characterized by a series of stages, each representing the employment of a successively refined approximation to the full Navier-Stokes equations that govern fluid motion. Relative to a preceding stage, each new stage incorporates additional physics, utilizes new numerical algorithms, requires significantly increased computer power, and results in an expanded range of practical application. Four main stages, with two important substages, stand out in their order of evolution and increased complexity:

<u>Stage</u>	<u>Approximation</u>
I	Linearized inviscid
Ia	Linearized inviscid plus boundary layer
II	Nonlinear inviscid (Euler)
IIa	Nonlinear inviscid plus interacting boundary layer
III	Reynolds-averaged Navier-Stokes
IV	Full Navier-Stokes (large eddy simulations with small scale turbulence modeling)

In each stage, computations historically have been made first for relatively simple two dimensional (2D) geometries, and subsequently developed for more complex 3D configurations.

The expanded range of practical application with each new stage is significant. With the linearized Stage I, for example, computations can be made of subsonic lift, induced drag, and pressure distribution for attached flow (e.g., subsonic cruise flight), and also of supersonic lift and wave drag for attached flow around slender bodies at small angles-of-attack. With the nonlinear Stage II, all the above computations can be made for transonic and hypersonic flow as well, and without the restriction of slender configurations. The addition of a boundary layer code (Stages Ia and IIa) enables skin friction

drag and improved pressure distributions to be computed. With the Reynolds-averaged Navier-Stokes Stage III, in which the turbulence momentum and energy transport terms must be modeled in the Navier-Stokes equations, all the above computations can be made plus those for separated flows, for large angles-of-attack, for interactions of external and engine exhaust flows, and for some unsteady flows such as airfoil buffet and aileron buzz. With the full Navier-Stokes Stage IV, in which the dominant turbulence transport terms are directly computed rather than modeled, computations of phenomena such as aerodynamic noise, transition, surface pressure fluctuations, and turbulence intensities can be added to the expanded list. Thus each new stage, relative to its preceding stage, represents a major advance in the range of practical utility of computational aerodynamics.

The present status of the different stages varies greatly, mainly because of the tremendous variation in computer power required for each stage. Stage I is now essentially mature. It underwent extensive R&D growth in the 1960s at which time computers then available had sufficient power to perform this stage of fluid dynamic computation effectively. As a result, Stages I and Ia have been used widely in practical aircraft design for over a decade. Stage II, on the other hand, is not as mature. Present computers of the Cray I or CDC 205 class have sufficient power for this stage; but the automatic generation of grid systems around complex aircraft configurations has not yet been perfected. Stage II has been used in practical aircraft design since the late 1970s, and is anticipated to reach maturity in the 1980s. Currently, Stage III is in a vigorous research and development mode limited mainly to relatively simple geometric configurations such as airfoils and bodies of revolution at angle-of-attack. The principal items pacing introduction of Stage III into the aerodynamic design process, beyond that of automatic grid generation, which is currently receiving much attention, are:

- (1) the development of improved turbulence models;*
- (2) the development of more powerful scientific supercomputers; and
- (3) the development of more efficient numerical algorithms.

These are described in detail in subsections II-2, II-3, and II-4 below.

With the projected development both of new supercomputers and of improved numerical methods, Stage III computations should be introduced in the aerodynamic design process to a limited degree during the present decade, and become widely used in the 1990s. In contrast, Stage IV is now only in an early pioneering research phase. Even for extremely simple flow geometries, such as a straight channel, a single run with Stage IV (which utilizes over a million grid points) can take 20- to 40- hours on the fastest current supercomputers. The long range potential of Stage IV computations, nevertheless, appears

*The boundary layer codes for Stages Ia and IIa would also profit from the development of improved turbulence models.

great since the major problem of Stage III, namely that involved in turbulence modeling, is simplified by directly computing the principal turbulence dynamics for each flow case. It is anticipated that Stage IV will enter its extensive R&D phase later this decade, but may not be used significantly in practical applications even near the end of the period covered by the present report. This stage is clearly paced by the development of much more powerful computers than are presently available. It is also paced by the development of a suitable model of small scale turbulence, particularly near the wall.

Both the United States and the major European countries have had considerable success in the practical exploitation of computational fluid dynamics. It has been used in Europe, for example, to develop better designs for new transport, business jet, and jet trainer aircraft. This capability for exploiting computational fluid dynamics compares fully with that in the United States since Europeans have both the expertise in numerical methods and the most powerful U.S. computers (Cyber 205, Cray 1S) with which to work. Russia, on the other hand, does not yet appear to have comparably powerful computers. This situation could change drastically, however, through Soviet acquisition of the most modern Japanese scientific supercomputers.

In summary, the overall evolution of computational fluid dynamics technology, which has been underway for about 15 years, is anticipated to continue for at least two decades more. This will provide progressively increased capabilities for the aerospace industry. Worldwide competition for the aircraft market is likely to become more intense as these methods are adopted overseas.

II-2. DEVELOPMENT OF TURBULENCE MODELING

The next major step in the advance of computational fluid dynamics will be Stage III, which uses the Reynolds-averaged Navier-Stokes equations. No terms in the Navier-Stokes equations are neglected, but those terms representing the time-averaged transport of momentum and energy by turbulence are modeled in a semi-empirical fashion. Uncertainties arising from transition and turbulence modeling form the primary limitations of this stage of computation.

A variety of methods for modeling turbulence in high speed flows have been under development over the past decade. Although notable progress has been made, improvement is needed. An overall perspective of the progress is provided by a comparison of the status of turbulence modeling in 1968 when the first international assessment was made (Ref. 1), with that in 1981 when the second such assessment was made (Ref. 2). In 1968 only 2D incompressible-flows with attached boundary layers were computed. In 1981 computations were made of 3D compressible flows containing separated regions. This progress is significant, although many shortcomings in the accuracy of turbulence modeling for these complex flows were revealed in 1981. Since the phenomena of fluid turbulence are extremely intricate and varied,

further notable progress should be made in the coming 10- to 15-years, but it is not anticipated that the problem of turbulence modeling will then be fully solved. It is expected that, as computer hardware and numerical methods improve, and as automatic grid generation methods are perfected, the main limitations of computational fluid dynamics with Stage III will arise from the inaccuracies of turbulence modeling. These limitations will affect the breadth and variety of practical applications to which such computations can be applied with confidence.

A realistic measure of the practical cost effectiveness of computational fluid dynamics is the cost per unit of flow information per unit of confidence in computed results. It is in the element of confidence that the state of turbulence modeling is so important. Computer costs per unit of information are now low, and will become very low with time. But confidence in the computed results for complex separated flows, such as those about fighter aircraft operating at large angles-of-attack, does not now exist. High confidence will require further improvements in turbulence models. This future development in modeling turbulence can have a major effect on the cost effectiveness of computational aerodynamics, just as can future developments in computer hardware and numerical algorithms.

It is further expected that a significant contribution to the development of improved turbulence models for use in Stage III will be made using guidance provided by research with Stage IV turbulence simulations. Flow fields for which results are sensitive to the location of transition present additional difficulties. While progress is being made in predicting transition locations for "standard" flight and wind tunnel disturbance environments, further developments are required to understand the effects of arbitrary environments on transition location. The same may be said about points of separation and reattachment.

II-3. DEVELOPMENT OF COMPUTER HARDWARE

The advance of computational fluid dynamics in coming years will be paced to a major degree by the rate at which the speed and memory of scientific supercomputers increase. Large supercomputers, which in the 1950s and 1960s comprised the primary computer market, and the driving force for new component technologies, now represent only a very small fraction of the overall computer mass market. With the market incentive greatly reduced, the rate of growth of U.S. supercomputer power has slowed during the past decade.

From the time the electronic computer was invented, the United States has clearly led in the manufacture of supercomputers. In 1983-84, however, a major new factor will emerge when Fujitsu of Japan introduces a new scientific supercomputer (FACOM VP200 Vector Processor) anticipated to be more powerful than any U.S. computer then available. Another comparable supercomputer from Hitachi is expected to be introduced not long thereafter. Thus, major foreign competition in making supercomputers has now emerged. The rate of growth of

supercomputer speed and memory in coming years may therefore be rejuvenated to some extent. At the same time, the clear superiority that the United States has long had in scientific supercomputer capability no longer exists.

Perhaps of even greater impact in the long term will be a Japanese supercomputer project of the Ministry for International Trade and Industry (MITI). By the end of the present decade the MITI goal is to develop a super high performance scientific computer, using new technologies such as gallium arsenide semiconductors and/or Josephson junctions. Their target for computational speed is the order of several score to several hundred BFLOPS (billions of floating point operations per second). Such speeds are 10 to 100 times the design speed of the NASA Numerical Aerodynamic Simulator (NAS), now planned for completion in 1987. If the MITI project is successful, its impact on future computer design, and on all major computational applications including aerodynamics during the 1990s, could be profound.

Future computer speed and memory, even with silicon technology, can be increased by a number of orders of magnitude before any fundamental physical limitations are encountered. Improvements will evolve from progressive increases in the density and area of silicon microelectronic chips. From an assessment of the anticipated trends in microelectronic technology, and from discussions with the major supercomputer manufacturers in the United States and Japan, a projection (Fig. 1) has been formed of the estimated growth in computer speed during the coming fifteen years. This projection is based on the expectation of the computer manufacturers that silicon technology will probably continue to be used throughout this period. The projected speed rises to about 10^4 MFLOPS in the late 1990s. This speed corresponds to an average vector processing speed representative of the needs of computational fluid dynamics codes.

To a first approximation, computer memory size has followed essentially the same trend as computer speed, with the order of 100,000 words of memory per MFLOP of speed. Future projections for semiconductor memory size are roughly parallel to those for speed, reaching about 500 Megawords by 1995 through use of 1-megabit memory chips.

Fortunately, the cost of computers has increased much more slowly than has performance. Past and projected trends in monthly rental cost are shown in Figure 1. Rental costs take into account inflation, and include maintenance and amortization costs. The net increase in computer cost has not been much greater than the increase due to inflation. Between 1955 and 1985, cost increases 10 times, whereas speed increases 10^4 times, producing a net improvement in computation cost effectiveness of 10^3 due to improvements in computer hardware. During the next 15 years this cost effectiveness should improve by another factor of about 30.

In view of the serious supercomputer R&D effort now taking place in Japan, the United States, as noted earlier, is no longer in a unique position as the world leader in supercomputer development. This raises a question of potential national importance, and of scope beyond that of the present study.

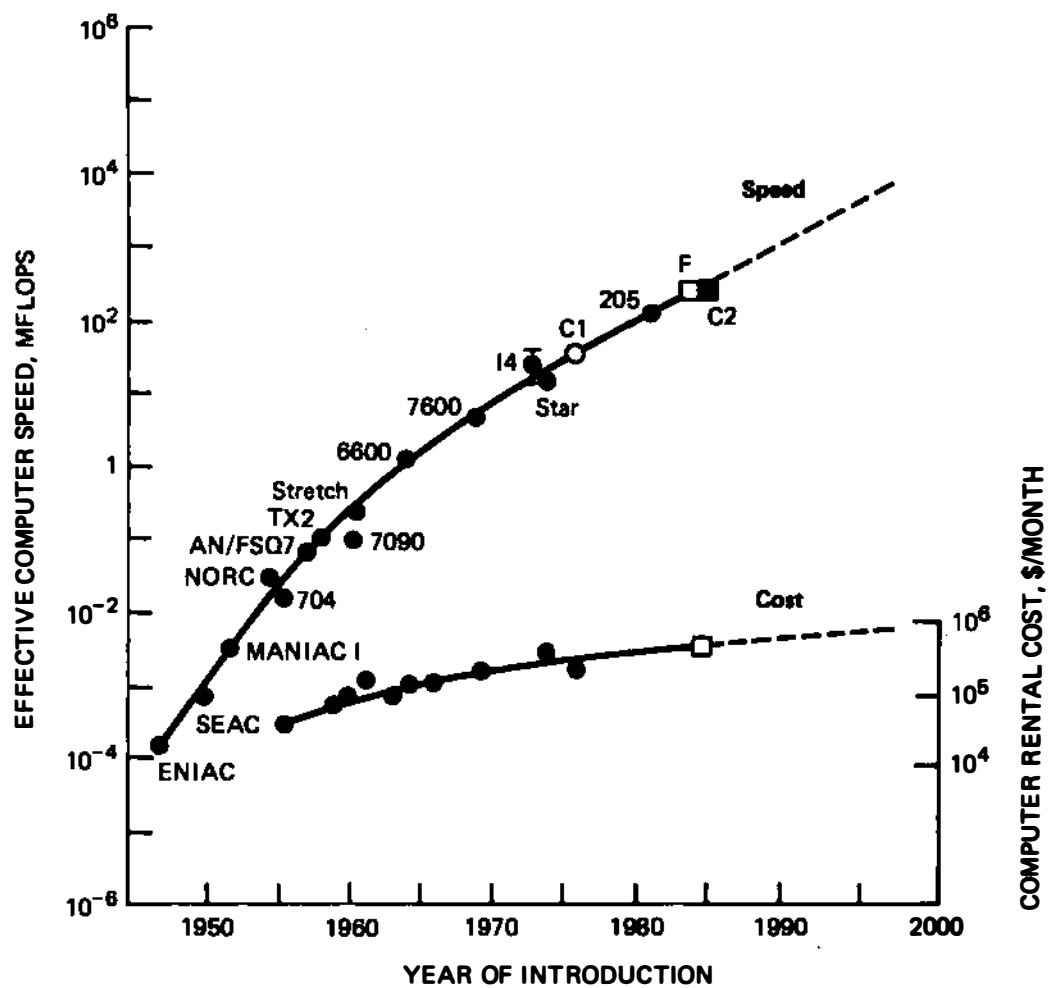


Figure 1 Past Growth and Future Projections for Computer Speed and Computer Cost.

The potential market does not provide enough incentive to maintain U.S. commercial leadership in the field. While computational fluid dynamics, in itself, may not provide the justification for U.S. leadership in supercomputer development, the committee is concerned about the impact of loss of U.S. leadership and urges that this issue be addressed at high levels in the government. In this regard, attention is drawn to the December 1982 National Science Foundation/Department of Defense Report of the Panel on Large Scale Computing in Science and Engineering, Peter D. Lax, Chairman, whose recommendations are endorsed by this committee.

II-4. DEVELOPMENT OF NUMERICAL METHODS

Resolution of the flow field about a complete aircraft configuration by numerically solving the Reynolds-averaged Navier-Stokes equations of Stage III would require about 2×10^6 to 9×10^6 grid points. Approximately 15-30 words of computer memory would be needed per grid point. Each component of the aircraft (wing, body, tail, nacelles, etc.) would be nested within its own grid chosen to resolve the significant viscous effects of turbulent flow. Each component grid would interface with an overall exterior stretched grid, extending far a way from the aircraft, chosen to resolve the essentially inviscid features of the outer flow. Substantial improvements in numerical methods will be required to make such calculations practical for aircraft design.

Much progress has been made in generating three-dimensional grids about complex body shapes. In recent years some wing-body-nacelle-pylon calculations have been made using the transonic small-disturbance and full-potential equations. Also, wing-body calculations have been made using the full Stage II Euler equations. Stage III numerical flow computations with a nested grid system, however, will require the development of new boundary condition procedures to couple the solutions calculated on separate grids. Such procedures are being worked on now and should be ready within the next few years.

Stage III calculations using existing implicit methods presently require several thousand iterations to converge. Although the time step increment that the solution can be advanced during each iteration is now orders of magnitude larger than that used formerly by explicit methods, it still requires many steps for information to be conveyed throughout the flow field. The time steps now chosen for accuracy of resolution in the field near a body are often inadequately small in the far field on stretched grids. Although implicit methods are continuing to improve, multigrid procedures now under intense study offer a higher potential for accelerating convergence. These procedures first form several coarse subgrids from an original fine grid, then calculate the solution on each using time steps scaled to the coarseness of the subgrid, and finally couple these solutions to the fine grid solution. In transonic flow calculations, multigrid procedures have reduced the number of iterations required for

convergence by more than an order of magnitude. For the Reynolds-averaged Navier-Stokes equations these procedures show promise of improving the efficiency of numerical methods by nearly two orders of magnitude.

In about five years, using the computers and numerical methods that will then be available, it should be possible to perform a Stage III research calculation for the flow about a complete aircraft configuration at flight Reynolds' numbers. Numerical methods at the research level should then be up to 5 times more efficient than at present. It may take another five to ten years, however, before this type of calculation can be used routinely in aircraft design. The curve in Figure 2 illustrates the past and projected improvements in the efficiency of numerical methods; and Figure 3 shows the trend in relative cost for computing a given flow with Stage III when the projected improvements in computer hardware are combined with the improvements in numerical methods. The resulting trend in decreasing cost to compute a given flow is extraordinary.

Although the United States is a leader in the development of computational fluid dynamics, we have no monopoly on expertise in this field. Knowledge of sophisticated numerical algorithms, as well as the methods for practical exploitation of computational fluid dynamics, exist widely abroad. Some of the major technical advances have, in fact, come from other countries; for example, finite element methods for complex aircraft configurations (France), efficient numerical methods for transonic flow (England), efficient multi-grid methods for a variety of flows (Israel), fractional step methods (Russia), and pioneering computations with Stage IV using the full Navier-Stokes equations (Germany). The western European countries, and Russia in particular, have long traditions of excellence in applied mathematics, and today participate fully in the science of numerical computation methods. This capability exists also in Japan, and is growing in China.

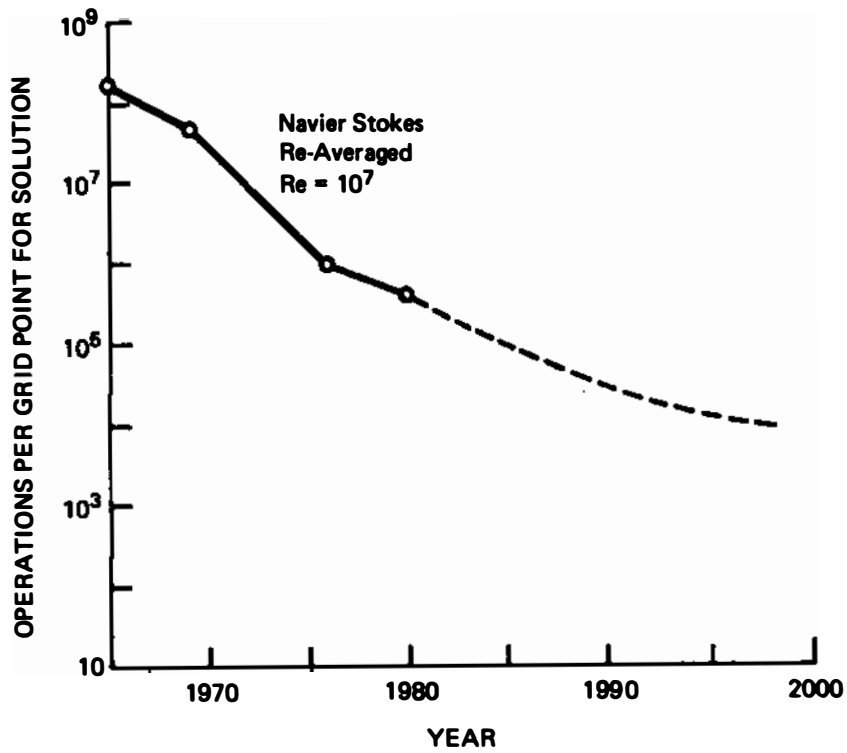


Figure 2 Past and Projected Improvements in Efficiency of Numerical Methods.

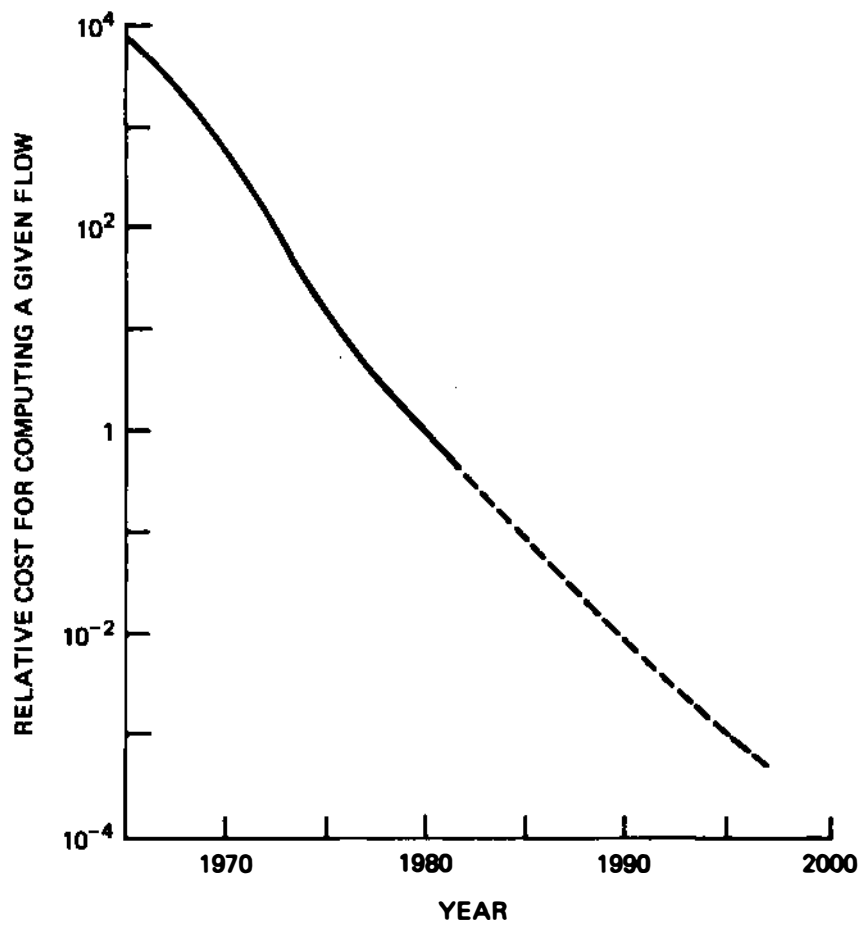


Figure 3 Past and Projected Decreases in Relative Cost of Navier-Stokes Numerical Computations for Stage III Considering Improvements both in Computer Hardware and in Numerical Methods. Cost Normalized to 1980; Reynolds Number 10^7 .

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III

Cost Considerations in Design: Test Facilities and CFD

To understand the factors determining the extent of CFD influence or test facility usage by the aerospace vehicle developer, it is necessary to recognize the unique economic forces at work within the U.S. aerospace industry. Dr. Alexander Flax gave an excellent, and still topical, survey of the situation in his 1974 Wilbur and Orville Wright Memorial Lecture (Ref. 1). The following paragraphs give some updating of his data, and discuss its significance in projecting the consequences of CFD development.

In the decade of the 1970s, all the major new aircraft programs (B747, C5A, F15, B1, L1011, DC10) reported wind tunnel occupancy times between 10,000 and 20,000 hours. Three major Boeing transport programs in the last one and one half decades used between 13,000 and 19,000 hours each. At an average cost of roughly \$1,500 per occupancy hour, the total wind tunnel occupancy cost for each program ranged between \$15 M and \$30 M. This is some fifty times greater than the average required for aircraft of the World War II era (Ref. 1).

Dr. Flax correctly attributes this enormous change to the cost risk entailed in the development effort. He points out the feedback effect; as developments have become more and more expensive, the developer companies and customers have called for more and more engineering analyses, design optimizations, wind tunnel and other engineering tests, in an effort to insure against the high financial risks. In turn, these additional engineering and test expenses have increased the financial exposure. The major aircraft programs of the 1970s, listed above, have development costs ("non-recurring program costs") between \$1 B and \$2 B, so large that they each place at risk the total assets of the entire corporation undertaking the development. The entire wind tunnel test program cost represents only some two percent of the total amount at risk. Although Dr. Flax did not discuss it, the major subcontractors, such as engine companies, are subject to equivalent risk and have correspondingly increased development costs.

This should not be assumed to imply that the developing company is not interested in economizing on test facility costs, or in any other part of the total engineering costs. There is, however, an overriding requirement for maximum confidence in the design. More specifically, the design team seeks to establish maximum confidence in the design at

the earliest possible time; for as the project continues, the financial exposure grows rapidly and the cost of recovering from a design error escalates. Under these circumstances, CFD, as a new technique for obtaining aerodynamic characteristics, will be assessed in accordance with the following four questions, in order of priority:

1. Does it increase confidence in the design, by giving true and accurate information on the aerodynamics of the full-scale vehicle throughout its flight envelope?
2. Is this information more complete, increasing assurance that there will be no potentially catastrophic aerodynamic characteristic overlooked in the design?
3. Will it offer earlier and more rapid evaluation of the aerodynamics of the proposed vehicle, so that needed changes can be incorporated at least cost?
4. Will it reduce the cost of obtaining aerodynamic data?

In responding to the first question, the most important matter of confidence, it must be recognized that the wind tunnel and engine test facility do not necessarily give true and accurate information applicable to the flight vehicle. Both are subject to undesirable flow disturbances and non-uniformity in the test area, and both have problems with interferences from the wall, the instrumentation and the supports of the test object. In addition, the small-scale models used in wind tunnel testing do not reproduce excrescences and surface condition (roughness, waviness), and almost invariably the test Reynolds' number is significantly less than in flight. The aerospace community has lived with these defects for several decades, however, and there is a vast amount of information on wind tunnel-flight differences and techniques for correction. Many experienced aerodynamic designers in industry and government laboratories are accustomed to applying suitable corrections for missing model details, wall and support effects, flow and Reynolds' number deficiencies. The background of experience of these designers gives considerable confidence in the validity of the corrected aerodynamic data.

As discussed in Chapter II, CFD has now reached the point where it is used in a number of design applications, particularly in Stages I and II. Nevertheless, the background of experience, the relation of CFD data to flight characteristics, is much too limited to permit confidence to the level required by the financial stakes. A steady build-up of confidence will occur over the next one or two decades, as CFD and wind tunnel data are accumulated together on the same configurations. This should not be regarded as unnecessary duplication; for while agreement between the two techniques will build confidence in CFD, it will also strengthen the company's confidence in the new design and in the validity of the wind tunnel data and corrections. More importantly, a discrepancy between the two results will alert the designer to possible trouble. This era of complementary test facility and CFD usage is examined in detail in Chapter IV below, and approximate time tables for different flow regimes are estimated.

The second question relates to the completeness of the information provided by wind tunnels or CFD methods. In principle, there is no question that computational methods can provide more complete information on the aerodynamic flow field than the most heavily instrumented practical wind tunnel model, since the computer can provide all aerodynamic parameters at every point of its grid network. This characteristic of CFD can be very valuable even at the present early stage, when the wind tunnel is the engineer's major tool; even now CFD can provide detailed diagnosis of the flow when the wind tunnel results indicate an unsatisfactory condition. As confidence in CFD methods grows, however, the designer will need methods of recognizing unsatisfactory or potentially dangerous flow characteristics quickly from the mass of computed data.

The third and fourth questions are not relevant for the period of time covered by this study, the next fifteen years. As we have seen, the test facility and CFD techniques can be expected to co-exist in a complementary role during this period; there may be some economies in the test facility program, but these will be offset by CFD costs. The prototype development schedule will be geared to the facility schedule, as in the past, until the designer gains sufficient confidence in CFD calculations to act upon them without waiting for experimental confirmation.

When this point is reached, the cost savings implicit in the third question are likely to be greater than those in the fourth, the direct comparison of data acquisition costs. To understand this, it must be appreciated that the present aerodynamic design is a multi-step process. There is an analytical step in which many compromises and optimization processes combine to give a configuration for tests. The next step is to build a model and test it. Almost certainly, the results will call for some changes; the model must be modified and re-tested. The engineer will often attempt to short-circuit this process by building his model with alternative components where his uncertainties are greatest--alternative nacelle positions to optimize interference, alternative engine inlets to compromise between performance at high and low angle-of-attack, for example--but with these exceptions the model's geometry is fixed, inflexible. In contrast, verification of design by CFD techniques in the future offers the possibility of immediate modification of the configuration geometry in the computer to correct an inadequacy or re-optimize locally, as long as the simulated boundary layer, separation, wakes and vortex effects change appropriately.

Put simply, the ultimate goal in CFD application must be to merge the two processes of aerodynamic configuration optimization and design verification. This not only permits a more complete optimization; by cutting out the delays inherent in model building and repeated wind tunnel test, it reduces greatly the chance of extensive--and expensive--design modification at a late stage in prototype development.

The preceding discussion implies that the aerospace companies make decisions on test facility and/or CFD utilization for their projects based on confidence in the information rather than on comparative

direct costs of generating the data. Nevertheless, in the course of its work the committee accumulated much information on elements of these costs; for completeness, this information has been collected together and included in Appendix D. When using this data, it should be remembered that the test facility capabilities and costs are for 1981-82, with computer support limited to that required for test data reduction. As detailed in Chapter V, one of the most effective ways to increase the capability and productivity of these facilities is to integrate with them a CFD capability. When this is done, the slight increase in operating cost per hour will be more than offset by the greater production of useful data.

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IV User Viewpoint

The engineering designer uses ground testing facilities and CFD methods to aid in configuration design of a wide variety of products. For example, conventional and advanced (supersonic) transports, military aircraft, helicopters and other V/STOL types of aircraft, airbreathing missiles, and re-entry type missiles and spacecraft are typical applications. The propulsion systems for these products, particularly gas turbine engines, are additional important areas of application.

Ground testing (e.g., wind tunnel or rig and engine testing) has had an advantage over CFD methods in the past in its ability to model more of the physics of the flow phenomena. However, there have been significant achievements in CFD modeling to the extent that the user (the engineering designer) can confidently rely upon these methods for certain aspects of design. As the user recognizes the value of CFD methods, he demands greater capabilities. These are the near-term challenges that the CFD method developers face. Both the CFD achievements to date and challenges that are faced today are discussed in Section 1 below.

What the user and funding organizations do not always realize is that the process of providing new CFD methods is not limited to the research accomplished in developing the enabling technology. At least three major phases can be identified for CFD development; these are elaborated in Section 2.

The aircraft designer currently views wind tunnel testing and CFD as complementary in the design and analysis of aircraft. This view is attributed to the fact that the strength of one tends to supplant the weakness of the other in the various details of configuration design. This aspect is discussed in Section 3.

What the aircraft designer requires for future CFD methods can be discerned by studying current wind tunnel development programs. These programs identify the configuration components critical for design and the applicable flow regimes (and hence, the areas where CFD could have a favorable impact). A discussion of the F-16 wind tunnel development program is provided in Section 4 to illustrate these considerations.

Those users designing gas turbine engines are at the cutting edge of technology in most of the engineering disciplines, including aerodynamics, combustion, structures, materials, life management, and

controls. This continuous stretching of experience boundaries invariably requires an extension of CFD capabilities and an extensive development program to achieve the utmost in engine performance, durability and reliability. The role of CFD in engine and missile design is discussed in Sections 5 and 6 respectively.

The full exploitation of CFD within the rotorcraft field depends upon the successful development of applications programs for the very complicated geometries and motions involved. Therefore, progress tends to be paced more by applications program development than by basic CFD capability.

IV-1. CFD ACHIEVEMENTS AND CHALLENGES IN THE DESIGN PROCESS

Computational aerodynamic simulation has evolved through an extensive range of capabilities. The following tabulation summarizes the history of aircraft design progression of CFD capability to date from the user's point of view. A parallelism can be drawn with the stages of development I through IV noted in Chapter II.

- (a) Subsonic and supersonic flow field around simple 3-D shapes (inviscid).
- (b) Subsonic and supersonic flow field around complex 3-D shapes (inviscid).
- (c) 2-D transonic flow field analysis (inviscid).
- (d) 3-D transonic flow field analysis (inviscid).
- (e) Boundary layer simulation and coupling of this simulation with above flow field analyses.
- (f) The representation of boundary layer separation criteria with the boundary layer operating in the 3-D flow field environment.
- (g) 2-D, subsonic, multi-element airfoil configurations (high-lift devices extended) including boundary layer simulation and the confluent and separated wake simulation of the multi-element configuration.

CFD technology is now facing the challenge of introducing the following more advanced computational capabilities.

- (h) Extending the multi-element viscous 2-D subsonic analysis to complex 3-D configurations, including the effects of large-scale flow separation (i.e., the prediction of maximum lift).
- (i) The more accurate simulations of viscous phenomena through the use of Reynolds-averaged Navier-Stokes solvers.
- (j) Analyses of flow fields incorporating strong vortex fields created by sharp wing leading edges, strakes and certain critical surface intersection geometries.

- (k) The difficult problem of establishing conditions where the boundary layer interacting with itself and/or the external flow field creates vortices having a high leverage effect upon the subsequent flow field.
- (l) On bodies, the similar effect of vortex peel-off due to merging boundary layers.
- (m) The complex effects associated with the coupling of elastic structures with non-steady viscous aerodynamic flows.

An important consideration in the computational analysis of engineering configurations is the representation of complex configuration geometry. The mathematical representation of complex geometry is a sophisticated technology in itself. For those computational analyses where flow field grid structures are required, the mathematics of grids can be very sophisticated, particularly for complex aircraft and engine shapes.

IV-2. THE THREE MAJOR PHASES OF CFD DEVELOPMENT

There are three major phases of the CFD development cycle, each contributing to the total process in an important way. These are depicted in Figure 4.

The first phase is the research phase where enabling technology is provided by individual contributors. It involves the conceptual development of the computational scheme, algorithm development, and testing by means of pioneering applications. The first phase ends when there is a high confidence that the technique will be successful. However, the actual structure of a useful software entity that has the potential of really useful applications is at its inception. The first phase is normally funded by NASA or other government agencies, and is implemented by government agencies, universities and certain segments of industry.

The second phase is the development phase which involves the production of a user-oriented method developed in a way to adequately address the engineering problems for which it was intended. This phase can be expensive and time consuming. In the past it has been government funded. However, in the present atmosphere of reduced government budgets, funding support for this type of CFD development work is in serious jeopardy. An additional factor is that this phase has not received the visibility it warrants according to its potential value to aircraft design. Industry, also operating under reduced budgets, will not be able to absorb the sharp decrease of the funding of such work. This work is long term in nature, benefits the entire aeronautical community, and is a growing factor in defense applications. This phase should also contain bench mark verification testing which is scrutinized by the community of expert technologists necessary to establish its readiness. It, therefore, is an appropriate area for federal stimulation and support.

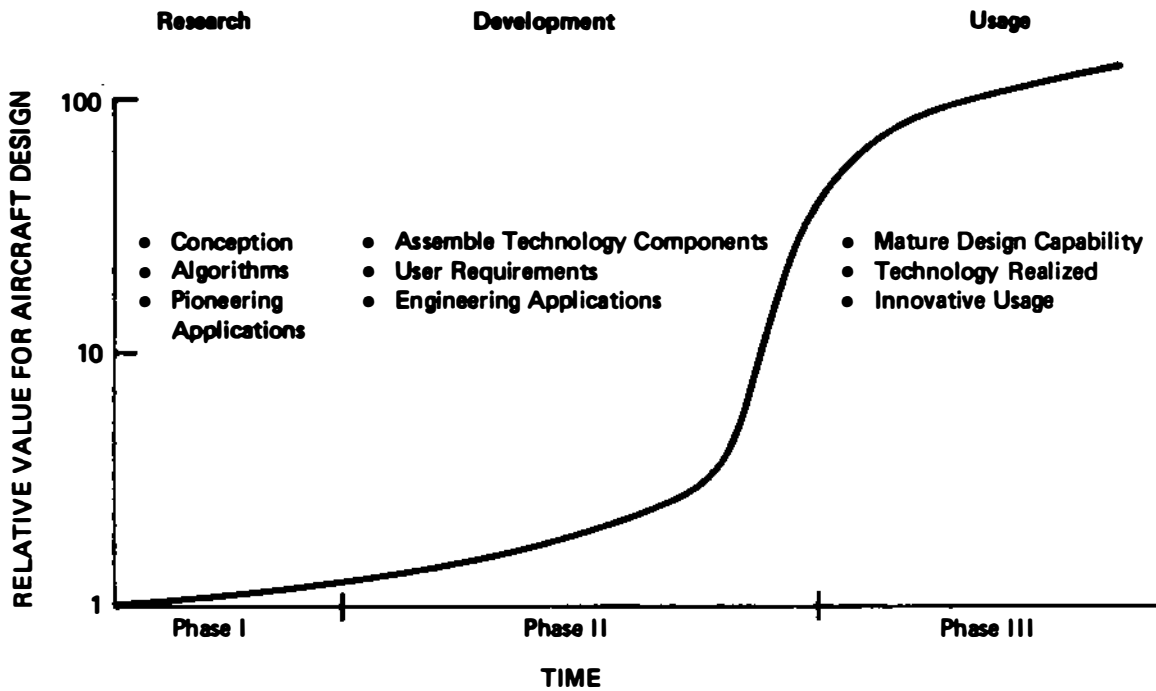


Figure 4 Development Cycle for a Major Computational Capability.

The third phase is the usage phase. This is the period where the user learns how to use the capability effectively, where many applications are investigated, where refinements are introduced based on usage, and where a maturing capability results in a high level of payoff (high value to aircraft design). This phase has been and should continue to be funded by the user (primarily industry). However, the success of phase three will hinge directly upon successful support and implementation of phase two.

IV-3. THE ROLE OF CFD IN AIRCRAFT DESIGN AND ANALYSIS

How wind tunnel testing and CFD contribute to the many elements of design and aircraft development are shown in Table 1. The relative strengths and weaknesses of each are presented along with an assessment of change by the end of the next 15 years. Design elements important to both commercial transport and military tactical aircraft are presented. This information makes it clear that the roles of wind tunnel testing and CFD are complementary in the design and analysis of aircraft, and these roles evolve as the capabilities of the two technologies develop. In considering the entire picture, some overall generalizations can be made.

- (a) Over at least the period of fifteen years considered in this study, the roles of CFD and the wind tunnel will be complementary, rather than competitive, because two entirely different techniques are involved. One is computational and the other is experimental; the insights, strengths and weaknesses, and adaptability to the problem at hand will always be quite different for the two processes.
- (b) CFD provides detailed insight, particularly in very local areas, as to how well the designer is meeting his objectives. This provides guidance for configuration options to be examined in the wind tunnel. Also, CFD provides diagnostic help in the understanding of problems that surface in wind tunnel testing. However, when integrated forces and moments are desired there are inherent mathematical inaccuracies associated with small differences of large numbers.
- (c) Wind tunnel testing allows a global integration of all the physics involved in the experiment. This means that integrated force and moment data are obtained directly by wind tunnel balance measurements. Although wall effects, low test Reynolds' numbers, and model mounting effects are influences with which one must contend, a carefully run wind tunnel experiment by an experienced engineer provides a great deal of meaningful information.
- (d) CFD allows a rapid analysis iteration of configuration modifications, providing a design optimization capability.
- (e) CFD can provide geometrical "design" information; that is, the shape required to provide a desired pressure distribution. This is the inverse of the normal task in computational work, a capability unique to CFD.

TABLE 1. RELATIVE STRENGTHS (AND WEAKNESSES) OF WIND TUNNEL TESTING AND CFD FOR AIRCRAFT DESIGN

SUBJECT	WIND TUNNEL	CFD	THE NEXT 15 YEARS
<p>CRUISE CONFIGURATION DEVELOPMENT</p> <p>o Wing Cruise Design</p>	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Provides confirmation that design objectives were met, e.g., drag level, drag rise, shock strength and location, desired longitudinal stability characteristics, and acceptable off design performance and stability levels. o Uncovers surprises in the physics of the flow that are impossible to detect from computational methods due to the simplified models used. o Flow visualization provides for diagnosis of global physical structure. o Reflects component interferences. o Large data base of earlier wings tested and large data base of wind tunnel to flight comparisons promote confidence in obtaining meaningful information. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Long lead times are required for testing a new configuration due to model construction and facility scheduling. o The various sources of drag (induced, wave, profile) are difficult to isolate. C Model flexibility, model support, and wind tunnel wall effects interfere with flow analysis. C Model wing aeroelastic representations are of limited scope due to cost. C Boundary layer transition must match full scale application for critical parameters as closely as possible. C Models deteriorate throughout testing due to handling, configuration changes, trip strip applications, and flow visualization (e.g., oil flows). C Tunnel configuration changes disrupt repeatability. C Reynolds numbers are low. M Wing leading edge line fidelity is occasionally a problem. 	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Provides more information about the entire flow field, and thus, leads to improved understanding of how a design can be improved. o Analysis flow time is fast and cost is low compared to wind tunnel testing. o Provides some information on individual drag components. o Valuable as a way to check wind tunnel interference effects. o Most critical regions of the wing can be identified and modified prior to testing. o Outstanding capability to model complex configurations in subsonic and supersonic flow. M Good prediction of shock location and strength, and drag increments. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Some physical phenomena are not adequately modeled or not modeled at all, e.g., discrete vortex effects due to strakelets or vanes. o Numerical algorithms are not yet mature enough to be completely reliable. o Drag calculation methods are neither well established nor reliable. o Aeroelastic characteristics are usually not represented. o Wake modeling is inadequate; wing-tail-canard interference is difficult to predict. C Poor prediction of shock location and strength. M Leading-edge features difficult to model with supersonic panel methods. 	<p>-----CFD-----</p> <ul style="list-style-type: none"> o Outstanding capability to model moderately complex configurations in transonic flow while accounting for viscous effects (good resolution on key components and major physical phenomena accounted for in steady flow). o Reliable algorithms for grid generation, Euler equation solvers, and boundary layer codes. o Improved reliability of drag calculation techniques. C Development of affordable Navier Stokes algorithms that can be used to improve understanding of complex viscous interaction phenomena. <p>-----wind tunnel-----</p> <ul style="list-style-type: none"> o Improved understanding of wind tunnel to flight correlation. o Full scale Reynolds number will be available at the National Transonic Facility (NTF). o Improved tripping techniques will allow better simulation of flight viscous effects.
<p>o Wing Nacelle Integration</p>	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Confirms basic installation effects. o Identifies problem areas involving strong viscous interactions. o Represents inlet and exhaust flows well. o Can determine drag components separately. o Local disturbances can be analyzed using pressure taps and flow visualization. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Costs are very high for powered tests. o Calibrations and test technique consistency requirements are very exacting. o Difficult to sort out thrust and drag contributors. C Half model tests are needed for accuracy. 	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Good design capability for contours, tilt, and toe-in in subcritical flows. o Ability to diagnose wind tunnel and flight results. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Limited capability in transonic flow. o Requires separate solution for internal and external jet flows. o Corner viscous flows and vortex formation not modeled. o Modeling of configuration is compromised by panel spacing. 	<p>-----CFD-----</p> <ul style="list-style-type: none"> o Well developed capability to model moderately complex configurations in transonic flow while accounting for viscous effects (good resolution on key components and major physical phenomena accounted for in steady flow). <p>-----wind tunnel-----</p> <ul style="list-style-type: none"> o Improved flow diagnostic techniques will allow better physical understanding.

Symbol denotes applicability: o - all aircraft, C - commercial transport, M - military tactical aircraft

TABLE 1. RELATIVE STRENGTHS (AND WEAKNESSES) OF WIND TUNNEL TESTING AND CFD FOR AIRCRAFT DESIGN

SUBJECT	WIND TUNNEL	CFD	THE NEXT 15 YEARS
<p>CRUISE CONFIGURATION DEVELOPMENT (cont.)</p> <ul style="list-style-type: none"> o Wing Buffet Margins and Stall Patterns 	<p>-----strengths-----</p> <ul style="list-style-type: none"> o The only practical tool available. o Successful techniques for predicting flight performance. o Provides insight into the dominant sources of global flow changes. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Interpretation of measured and visualized results are often difficult, since the effects are unsteady. o Difficult unobtrusively to visualize associated flow fields. o Model wing aeroelastic representations are of limited scope due to cost. o Advanced airfoils and radical configurations may not fall into current empirical techniques. 	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Provides guidance on incipient separation pattern prior to testing; allows redesign for delaying separation. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o The complex, viscous, vortex dominated flow fields cannot now be adequately calculated for other than the most simple geometries. o Methods do not handle high angle of attack conditions where shock strengths are high and boundary layers separate. 	<p>-----CFD-----</p> <ul style="list-style-type: none"> C Navier Stokes solvers will provide a better understanding of the physical phenomena occurring in the flow. C Navier Stokes solvers may enable us to classify a small number of flow patterns and develop simpler and cheaper models. <p>-----wind tunnel-----</p> <ul style="list-style-type: none"> o Improved flow diagnostic techniques will allow better physical understanding. o More empirical correlation between flight and wind tunnel will be obtained.
<ul style="list-style-type: none"> o Total Configuration/Integration and Drag Assessment 	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Final design reached through iterative wind tunnel tests. o Adequately predicts flight performance and stability levels. o Identifies physical phenomena associated with component integration. o Provides good indication of total configuration drag. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> C Limited cause and effect information provided for component interaction. C Reynolds number effects, especially on stability, requires ad hoc approaches. C Different trip strip configurations needed. C All component drag buildup required. 	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Can analyze moderately complex configurations in subsonic and supersonic flows. o Permits better understanding of cause and effect relationships for component interaction. o Can provide insight into model mounting and wind tunnel interferences. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Transonic flow analysis of complex configurations not well developed. o Complex viscous interactions not simulated. o Absolute levels of performance (drag) and stability not reliable. 	<p>-----CFD-----</p> <ul style="list-style-type: none"> o Well developed capability to model moderately complex configurations in transonic flow while accounting for viscous effects (good resolution on key components and major physical phenomena accounted for in steady flow). C Navier Stokes solvers will be used to analyze phenomena on isolated parts of the configuration using zonal imbedding techniques. <p>-----wind tunnel-----</p> <ul style="list-style-type: none"> o Improved understanding of wind tunnel to flight correlation o Full scale Reynolds number will be available at NTF.
<ul style="list-style-type: none"> o Detail Refinement (e.g., Cab Shape) 	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Provides confirmation that design objectives were met. o Fast, crude changes are possible to make and evaluate during a test. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> C Provides limited knowledge on how to improve design details. C Difficult to maintain quality of changes made to a model during a test. C Difficult to save contours associated with a model changed during a test. 	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Provides good understanding of the detailed flow and guidance on how to improve the configuration. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Absolute drag levels are not reliable. o Subject to surprise from occurrences where physics were not modeled. 	<p>-----CFD-----</p> <ul style="list-style-type: none"> o Significantly improved geometry programs will aid the user in defining complex shapes, including intersections, and then in obtaining extractions for analysis programs. C Navier Stokes solvers will be used to analyze phenomena on isolated parts of the configuration using zonal imbedding techniques. <p>-----wind tunnel-----</p> <ul style="list-style-type: none"> o Full scale Reynolds number will be available at NTF.

TABLE 1. RELATIVE STRENGTHS (AND WEAKNESSES) OF WIND TUNNEL TESTING AND CFD FOR AIRCRAFT DESIGN

SUBJECT	WIND TUNNEL	CFD	THE NEXT 15 YEARS
CRUISE CONFIGURATION DEVELOPMENT (cont.) o Cowl and Nozzle Design (External Aerodynamics)	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Extensive experience and expertise in this type of testing. o Identifies "real" flow effects o Can determine drag by direct force and momentum deficit methods. o Flow visualization is useful for determining flow direction, separated flow, and vortex formation. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Low Reynolds number testing may lead to conservative design. o Blowing drag tests are expensive. o Susceptible to errors; requires a statistical approach (repeatability). o Small model parts require accurate machining. o Models are complex, and testing is difficult. o Isolated and installed testing required to get all interference drag terms. o Calibrations needed for internal drag. o Difficult to sort out thrust and drag contributors. 	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Good exterior and interior analysis capability for isolated nacelles in transonic flow. M Supersonic sidewash/upwash calculations for inlet location is reasonable. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Plume modeling inadequate. o Inaccurate shock location on cowl. o Difficult to simulate nozzle effects. 	<p>-----CFD-----</p> <ul style="list-style-type: none"> o Well developed analysis capability for arbitrary nacelle shapes mounted on wing-body-strut configurations in transonic flow. <p>-----wind tunnel-----</p> <ul style="list-style-type: none"> o Full scale Reynolds number will be available at NTF for flow-through models.
CRUISE STABILITY AND CONTROL o Basic Cruise Stability	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Adequate capability. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Sensitive to Reynolds number, support, and boundary layer transition techniques. 	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Good for linear derivatives (orbiter on 747) in subsonic and supersonic flow. o Predicts steady aeroelastic effects. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Fails to predict nonlinear phenomena. 	<p>-----CFD-----</p> <ul style="list-style-type: none"> C Good separated flow models. C Transonic inviscid calculations of derivatives routine. <p>-----wind tunnel-----</p> <ul style="list-style-type: none"> o Full scale Reynolds number will be available at NTF.
o Stability at Extreme Conditions (high angle-of-attack and Mach number)	<p>-----strengths-----</p> <ul style="list-style-type: none"> o The only useful pre-flight technique in wide-spread use. o Provides insight into the dominant sources of global flow changes. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Interpretation of measured and visualized results is often difficult, since the effects are unsteady. o Unable to visualize associated flow fields. o Reynolds number deficiencies. o Extremely time consuming for full data base. 	<p>-----strengths-----</p> <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o No capability. 	<p>-----CFD-----</p> <ul style="list-style-type: none"> o Euler equation solvers coupled with boundary layer calculations and empirical separation models will provide a significant capability. o However, no capability to analyze complete configurations in a Navier Stokes solver. <p>-----wind tunnel-----</p> <ul style="list-style-type: none"> o Full scale Reynolds number will be available at NTF.

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Symbol denotes applicability: o - all aircraft, C - commercial transport, M - military tactical aircraft

TABLE 1. RELATIVE STRENGTHS (AND WEAKNESSES) OF WIND TUNNEL TESTING AND CFD FOR AIRCRAFT DESIGN

SUBJECT	WIND TUNNEL	CFD	THE NEXT 15 YEARS
CRUISE STABILITY AND CONTROL (cont.) o Dynamic Stability	-----strengths----- M Traditional tool for this information. M Provides satisfactory results. -----weaknesses-----	-----strengths----- -----weaknesses----- M No capability.	-----CFD----- M No appreciable change from today. -----wind tunnel----- M New rig in the AMES 12 foot tunnel will increase Reynolds number at subsonic speeds.
o Control Surface Effectiveness	-----strengths----- o Best tool for this information. -----weaknesses----- o Reynolds number effects may be large in many cases.	-----strengths----- o Provides some limited capability. o Can account for some steady aeroelastic effects. -----weaknesses----- o Results are not always reliable.	-----CFD----- C Navier Stokes solvers will include separation effects. -----wind tunnel----- o Full scale Reynolds number will be available at HTF.
o Control Surface Hinge Moments	-----strengths----- o Best tool for this information. -----weaknesses----- o Reynolds number effects may be large in many cases.	-----strengths----- o Provides some limited capability. o Predicts steady aeroelastic effects. -----weaknesses----- o Results are not reliable.	-----CFD----- -----wind tunnel----- M Occasionally deemphasized due to subscale demonstrator.
o Device Refinement (Vortex Generators, Fences, etc.)	-----strengths----- o This is the best method for devising these types of fixes. o Verifies real flow effects. o Good agreement between wind tunnel and flight test has been demonstrated for vortex generator effects. o More recent flow visualization techniques have been valuable for understanding effects of devices. -----weaknesses----- o Reynolds number constraints make proper design laborious and difficult. o Lack of proper physical understanding and inadequate flow diagnostic tools make the cut and try approach difficult.	-----strengths----- o Provides guidance concerning local flow directions for device alignment. o Can simulate flight Reynolds numbers. -----weaknesses----- o Cannot predict complex viscous phenomena. o Cannot model discrete vortex effects in subsonic or transonic flow.	-----CFD----- o Navier Stokes solvers will greatly improve predictive capability in this area. -----wind tunnel----- o Improved physical understanding, flow visualization methods, and flow diagnostic techniques will provide the basis for a more efficient and systematic design approach.

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TABLE 1. RELATIVE STRENGTHS (AND WEAKNESSES) OF WIND TUNNEL TESTING AND CFD FOR AIRCRAFT DESIGN

SUBJECT	WIND TUNNEL	CFD	THE NEXT 15 YEARS
<p>HIGH LIFT SYSTEM DEVELOPMENT</p> <ul style="list-style-type: none"> o Exploration of Trades, Various High Lift Devices 	<p>-----strengths-----</p> <ul style="list-style-type: none"> o The only tool available for obtaining good answers. o Large data base of high lift system evaluations in tunnels. o Extensive experience and expertise in this type of testing. o Data base of wind tunnel to flight test comparisons. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o It is difficult to install accurately some model parts due to their small size. o Uncertainties due to Reynolds number effects may distort trades. o Many test configurations are required to accomplish trades. o Mounting system interferences are not well understood. o Because of model scale, most of high lift excrescences (and-treatment, fixed leading edge cutouts, support interferences, leakages, and aeroelastic effects) cannot be studied meaningfully. o Off-body flow visualization methods are inadequate. 	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Can be utilized to eliminate unfruitful configuration possibilities. o Lifting line methods are ideal for trade studies; they show primary aerodynamic effects, and are simple and cheap to use. o Two dimensional methods are useful for tailoring sections. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Flaps down wing wake is not realistically modeled. o Complex viscous effects are not included. o Nacelle or thrust effects are generally not included. 	<p>-----CFD-----</p> <ul style="list-style-type: none"> o Refined process for calculating realistic pitching moments for the highly viscous flows (tail on and tail off). <p>-----wind tunnel-----</p>
<ul style="list-style-type: none"> o Assessment of Maximum Lift Levels, Various Flap Deflections 	<p>-----strengths-----</p> <ul style="list-style-type: none"> o The only tool available for obtaining good answers. o Good global results can be obtained at many angle-of-attack and flap deflection conditions. o Flow visualization by means of tufts can be helpful. o Large data base of configurations tested. o Valuable even if only used incrementally. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Can give misleading results at wind tunnel Reynolds numbers. o Does not provide much guidance as to which flow details limit performance. 	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Can be utilized to eliminate unfruitful configuration possibilities. o Predicts maximum lift as a function of Reynolds number reasonably well for current technology wings. o A limited design (inverse) capability exists. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Improvements are needed in modeling three-dimensional separation, particularly for complex geometries. 	<p>-----CFD-----</p> <ul style="list-style-type: none"> o Navier Stokes solvers will be very valuable in enabling us to pin down the phenomena initiating breakdown. This will enable us to do local tailoring to improve maximum lift. Also, these solvers will provide insight into the progression of stall patterns and enable us to control pitchup. <p>-----wind tunnel-----</p> <ul style="list-style-type: none"> o Improved flow diagnostic techniques will allow better physical understanding.
<ul style="list-style-type: none"> o Assessment of Aircraft Drag at High Lift, Various Flap Deflections 	<p>-----strengths-----</p> <ul style="list-style-type: none"> o The only tool available for obtaining good answers. o Good global results can be obtained at many angle-of-attack and flap deflection conditions. o Can simulate ground effects. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Does not provide much guidance as to which flow details limit performance. o Rely on semi-empirical methods to help determine flight polars. o High Reynolds number testing limited by cost. 	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Can be utilized to eliminate unfruitful configuration possibilities. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Capabilities are quite limited. 	<p>-----CFD-----</p> <ul style="list-style-type: none"> o Better insight into drag contributors will be possible (although total drag prediction will still be unreliable). <p>-----wind tunnel-----</p>

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TABLE 1. RELATIVE STRENGTHS (AND WEAKNESSES) OF WIND TUNNEL TESTING AND CFD FOR AIRCRAFT DESIGN

SUBJECT	WIND TUNNEL	CFD	THE NEXT 15 YEARS
<p>HIGH LIFT SYSTEM DEVELOPMENT (cont.)</p> <ul style="list-style-type: none"> o Buffet Margins, Stall Patterns, and Stability at High Lift Levels 	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Provides insight into the dominant sources of global flow changes. o Identifies "real" flow effects. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Interpretation of measured and visualized results are often difficult, since the effects are unsteady. o Unable to visualize associated flow fields. o Reynolds number effects are difficult to understand. o Aeroelastic effects are not modeled. 	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Good for initial design guidance, post design refinement, and re-design guidance for high aspect ratio wings. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o The complex, viscous, vortex dominated flow fields cannot now be adequately calculated for other than the most simple geometries. 	<p>-----CFD-----</p> <ul style="list-style-type: none"> C Navier Stokes solvers will provide a better understanding of the physical phenomena occurring in the flow. <p>-----wind tunnel-----</p> <ul style="list-style-type: none"> o Improved flow diagnostic techniques will allow better physical understanding.
<ul style="list-style-type: none"> o Engine-out Performance Assessment 	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Good for drag due to controls, sideslip, and inlet spillage. o Can model engine windmilling to measure high spillage drag. o Pressure taps and flow separation help establish areas of cowl separation. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Uncertainties due to potentially large Reynolds number effect. o Flight engine windmilling drag cannot be accurately predicted, since models use plates for blockage. 	<p>-----strengths-----</p> <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Unreliable due to complex nature of drags, which are partly induced and largely viscous sensitive. 	<p>-----CFD-----</p> <p>-----wind tunnel-----</p>
<ul style="list-style-type: none"> o Low Speed Control Effectiveness 	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Useful in establishing probable capability. <p>-----weaknesses-----</p>	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Useful capability available. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Viscous effects are not organized or standardized. 	<p>-----CFD-----</p> <p>-----wind tunnel-----</p>
<ul style="list-style-type: none"> o Low Speed Control Hinge Moments 	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Traditionally the only reliable approach. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Great care must be taken to represent boundary layer effects appropriately (e.g., large scale partial models). 	<p>-----strengths-----</p> <p>-----weaknesses-----</p>	<p>-----CFD-----</p> <p>-----wind tunnel-----</p> <ul style="list-style-type: none"> M Occasionally de-emphasized due to subscale demonstrator.

Symbol denotes applicability: o - all aircraft, C - commercial transport, M - military tactical aircraft

TABLE 1. RELATIVE STRENGTHS (AND WEAKNESSES) OF WIND TUNNEL TESTING AND CFD FOR AIRCRAFT DESIGN

SUBJECT	WIND TUNNEL	CFD	THE NEXT 15 YEARS
AIRLOADS o Aircraft Surface Pressure Distributions Versus Angle-of-Attack and Mach Number	-----strengths----- o Accurate. o Provides major insights before flight loads measurements. -----weaknesses----- o Very expensive and time consuming. o Must be positioned well in advance of the test. o Results can be misleading if scale effects are not properly simulated. o Occasionally limited by pressure tap resolution. M Unable to test for rapid maneuvers.	-----strengths----- o Pressure distributions are calculated by most methods. o Predicts steady aeroelastic effects. -----weaknesses----- o Validity is related to adequacy of modeling (no value at high angle-of-attack where many critical design cases are found).	-----CFD----- o Capability will be improved due to our ability to model more types of flows. -----wind tunnel----- o Advances in Laser Doppler Anemometer systems will reduce costs and time in obtaining velocity (and hence pressure) measurements.
o Integrated Component Loads (Nacelle Loads at Strut, High Lift Device Loads, etc.)	-----strengths----- o Used universally. -----weaknesses----- M Unable to test for rapid maneuvers (e.g., horizontal tail loads in rapid pull-up).	-----strengths----- o Cruise loads are reasonably calculated. -----weaknesses----- o Not good at design load conditions.	-----CFD----- -----wind tunnel-----
FLUTTER o Dynamic Airloads (Gust and Buffet Loads), Divergence, and Control Buzz	-----strengths----- o The best tool for this information. o Represents all general flow characteristics required for flutter modeling. -----weaknesses----- o Low Reynolds numbers affect separated flow induced flutter occurrences. M Freon effects on stall are uncertain. M Transition fixing in Freon is uncertain. M Gust loads/buzz testing not traditional.	-----strengths----- M Panel methods are the traditional tool for this type of information (except for buffet loads). M Results are fairly good. M Some capability for divergence. -----weaknesses----- M Unsteady panel methods may need leading edge separation and shed vortex models. M There are no buffet forcing functions for panel methods.	-----CFD----- o Well developed capability for unsteady transonic flow analysis using full potential equation solvers. o Emerging capability for unsteady Euler analysis. -----wind tunnel----- o Existing facilities will be used more for flutter analysis to get broader Mach number range. o New techniques will be developed in the way of parameter identification to better understand the onset of flutter. o Empirical models will be developed to aid design. o Reynolds number simulation will improve.
SPECIAL STUDIES o Wake Vortex Studies	-----strengths----- -----weaknesses----- C Testing is difficult due to the enormous length scales that are needed in order to simulate trailing vortex flow and decay.	-----strengths----- C Some ability to predict effects on trailing aircraft. -----weaknesses----- C Viscous decay of vortices not well modeled.	-----CFD----- -----wind tunnel-----

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TABLE 1. RELATIVE STRENGTHS (AND WEAKNESSES) OF WIND TUNNEL TESTING AND CFD FOR AIRCRAFT DESIGN

SUBJECT	WIND TUNNEL	CFD	THE NEXT 15 YEARS
<p>SPECIAL STUDIES (cont.)</p> <ul style="list-style-type: none"> o Flow Visualization (surface, flow field) 	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Good standard techniques for surface flows at all Mach numbers. o Identifies the occurrence of complex phenomena. o Indicates shock strength, flow separation, flow direction, vortices, and transition. o Can vary Mach number and angle-of-attack continuously while watching visualization. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Little value for flow field diagnosis at transonic Mach numbers. o Frequently difficult to decipher exactly what is going on. o Surface flows give the limiting streamline and not the direction of the adjacent outer flow. o Nonobtrusive flow field capability is quite poor. o Tufts deteriorate. o Oil flows clog pressure taps. 	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Provides valuable insights for flow fields that are adequately modeled. C Streamline tracing capability is a valuable design aid. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Of little significance in current project work. o Streamline tracing not available in many codes. 	<p>-----CFD-----</p> <ul style="list-style-type: none"> o Capability will be improved due to our ability to model more types of flows. <p>-----wind tunnel-----</p>
<ul style="list-style-type: none"> o Natural Laminar Flow 	<p>-----strengths-----</p> <ul style="list-style-type: none"> C Wind tunnel tests are free from simplifying assumptions. C All the known and unknown nonlinear effects are present. C Recent NASA Langley work on 8 foot Pressure Wind Tunnel (PWT) has provided a unique facility, the best in the world, for NLF experiments. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> C Flow disturbances that trigger turbulence may be different from actual flight. C Reynolds number differences may cause transition modes to be different. C Need to change the 8 foot linings for each test at the PWT. C Cannot test full configurations at the PWT. 	<p>-----strengths-----</p> <ul style="list-style-type: none"> C Provides insight into experimental results without which transition data are almost incomprehensible. C Linear stability theories have provided the best method of correlating experimental transition data. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> C Complexity of theory allows only limited nonlinear effects to be considered. 	<p>-----CFD-----</p> <ul style="list-style-type: none"> C Nonlinear stability theories should be well developed. <p>-----wind tunnel-----</p> <ul style="list-style-type: none"> C The NASA Langley 8 foot Pressure Wind Tunnel will become the workhorse of laminar flow research. C Data from this tunnel should provide an adequate data base for NLF airplanes.

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TABLE 1. RELATIVE STRENGTHS (AND WEAKNESSES) OF WIND TUNNEL TESTING AND CFD FOR AIRCRAFT DESIGN

SUBJECT	WIND TUNNEL	CFD	THE NEXT 15 YEARS
SPECIAL STUDIES (cont) o Laminar Flow, Active Systems	<p>-----strengths----- C Real flow simulation by wind tunnels is essential due to complexity of transition modes in active laminarization systems.</p> <p>-----weaknesses----- C Scaling problems are more difficult. C Model fabrication is difficult and expensive. C Less freedom to compensate small model sizes with high unit Reynolds numbers. C Reynolds number limitations at the NASA 8 foot Pressure Wind Tunnel prevent testing entire configurations.</p>	<p>-----strengths----- C Provides insight into experimental results without which transition data are almost incomprehensible. C Linear stability theories have provided the best method of correlating experimental transition data.</p> <p>-----weaknesses----- C Complexity of theory allows only limited nonlinear effects to be considered.</p>	<p>-----CFD----- C Nonlinear stability theories should be well developed.</p> <p>-----wind tunnel----- C The NASA Langley 8 foot Pressure Wind Tunnel will become the workhorse of laminar flow research. C Data from this tunnel should provide an adequate data base for MLF airplanes.</p>
o Weapons Integration	<p>-----strengths----- M Extensive experience and expertise in this type of testing. M Best tool for this information.</p> <p>-----weaknesses----- M Reynolds number effects may be large in many cases. M Very expensive and time consuming.</p>	<p>-----strengths----- M Qualitative information for carriage aerodynamics, separation, and delivery using panel methods.</p> <p>-----weaknesses-----</p>	<p>-----CFD-----</p> <p>-----wind tunnel-----</p>
o Maneuvering Performance	<p>-----strengths----- M Traditional tool for this information. M Provides good results.</p> <p>-----weaknesses----- M No method for fixing transition for some wing concepts. M Model support and wind tunnel wall effects interfere with flow analysis. M Buffet intensities interfere with flow analysis.</p>	<p>-----strengths----- M Some help for configuration refinement in attached flow (pressure distribution trends).</p> <p>-----weaknesses----- M No capability for drag or pitching moment calculations, or wing concepts having separated flow regions.</p>	<p>-----CFD-----</p> <p>-----wind tunnel----- M Better understanding of Reynolds number effects. M Routine testing at higher Reynolds numbers.</p>

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- (f) Flow visualization, of sorts, can be obtained through wind tunnel testing or CFD, but the practical techniques and practical application of flow visualization are far more developed and useful from the wind tunnel.
- (g) When an aerodynamic effect of significance has been encountered, either in CFD or wind tunnel testing, the effect is often studied from the other perspective as well, to gain the most possible understanding.
- (h) Once a wind tunnel model is built for a final configuration, the collection of "data base" information (for performance, stability and control, and airloads) is efficiently accomplished in the wind tunnel, particularly when considering the large numbers of conditions required (Mach numbers, angles-of-attack).
- (i) During the next 15 years, computation of vortex and viscous flows will provide a vastly improved theoretical description of the flow fields. Development of Navier-Stokes solvers will help in modeling local regions of separated flow. However, the lack of adequate modeling of turbulence may stand in the way of a complete flow field analysis.

IV-4. THE DISTRIBUTION OF TYPE OF ANALYSIS IN THE DESIGN OF AN AIRCRAFT

Insight can be gained on a large variety of requirements for computational analysis by studying the distribution of work in wind tunnel development programs. The F-16 is an example of a product which required the study of a large variety of configuration components and a large variety of flow field types.

The F-16 is a high-technology, modern fighter aircraft. In this program, a total of nearly 12,000 hours of wind tunnel testing was accomplished over a period from 1971 to 1982. The aircraft represents a high degree of aerodynamic technology for this time period. Although fighter aircraft operate normally in a greater variety of flow fields than do commercial transports, this aircraft is not designed for STOL capability, and thus, it does not have such other complex design features as highly tuned, high-lift systems and/or propulsive system interactions for vectored thrust and thrust reversing.

Figure 5 presents a test summary of the F-16 program broken down into major test requirements through the evolution of the configuration, and its introduction as an operational, first-line fighter. The chart also shows the number of test hours in each of the categories for the subsonic, transonic, and supersonic test regimes. These results show that a great deal of emphasis was placed, during the wind tunnel development, on transonic testing and on high angle-of-attack testing in the spin, stall, and controllability areas. This emphasis is typical of high-performance fighter aircraft.

An attempt has been made to relate the wind tunnel testing for the F-16 program, as shown in Figure 5, to flow regimes with increasing degrees of complexity. A summary of this information is shown in

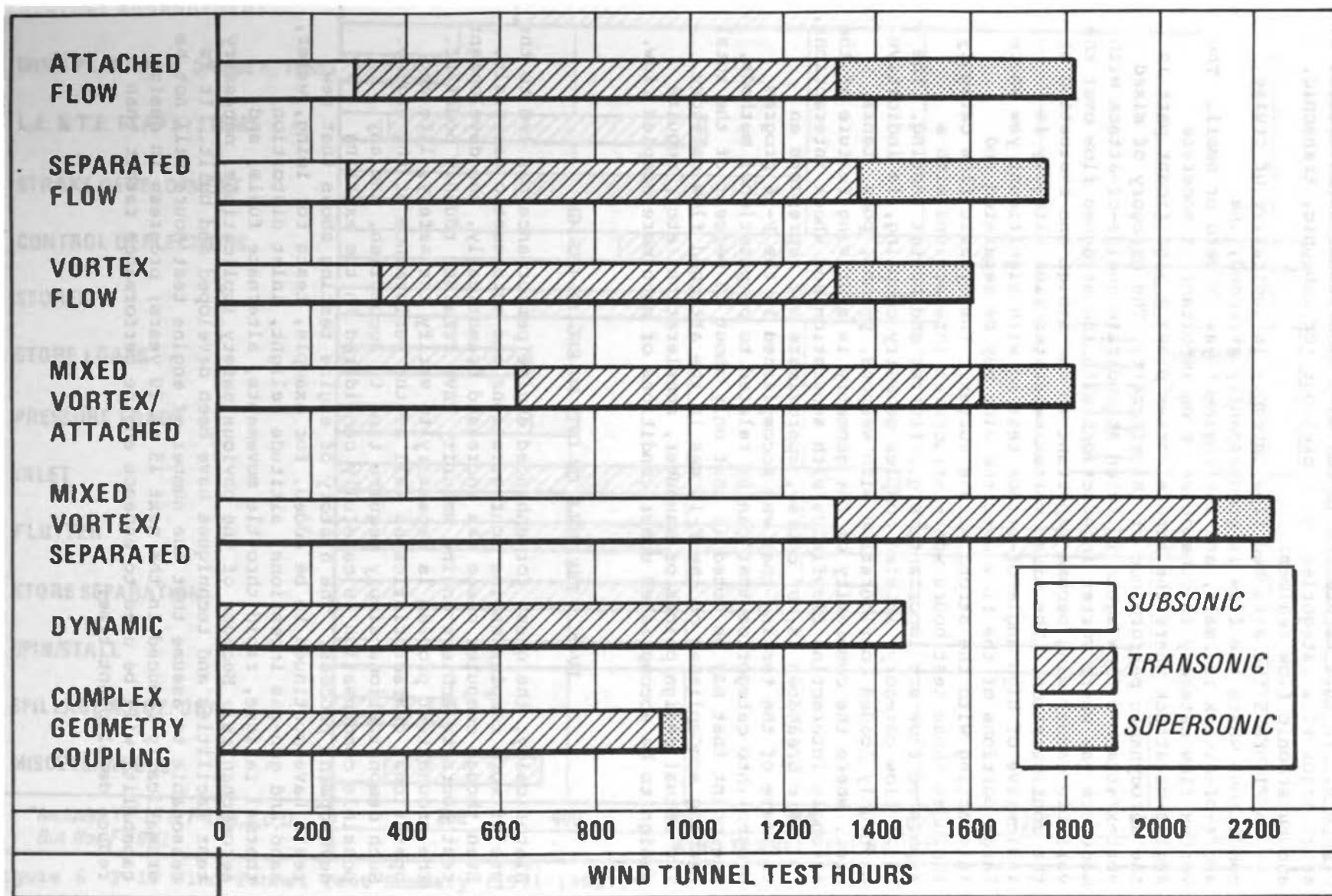


Figure 5 Breakout of F-16 Wind Tunnel Testing by Flow Field Complexity.

Figure 6. In this figure the approximate wind tunnel hours related to seven major flow categories are broken out for subsonic, transonic, and supersonic flow regimes.

In Figure 5 the attached flow category is indicative of cruise conditions where the flow is predominantly attached, the angle-of-attack is small, and the angle-of-yaw is zero or small. The vortex flow category is considered to be important at moderate angles-of-attack where the strake vortex plays a significant part in the aerodynamic performance of the aircraft. The category of mixed vortex/attached flow again is taken at moderate angles-of-attack with moderate yaw where vortex interactions with the attached flow over the variable camber wing become important in the design and evaluation of the configuration. The mixed vortex/separated flow category is indicative of high angle-of-attack testing with significant yaw where large portions of the flow over the wing may be separated and interacting with the strong strake vortex. The dynamic flow category includes those test hours where structural interactions with a separated flow are important, e.g., flutter and buffet testing. The final flow category, labeled complex geometry coupling, is indicative of highly loaded configuration with weapons, pylons, pods, tanks, etc., where the complexity of the geometry is a driving feature of the strongly interacting flowfields with separation and shock interactions.

This breakdown is, of course, approximate but represents an estimate of the testing that was accomplished in the F-16 program broken into categories that can be related to computational methods. One point that may be noted is that only about 15 percent of the total testing accomplished on the F-16 was in the attached flow category. The actual design points of maneuver, acceleration, etc., require design to be accomplished under conditions of much more complex flow.

IV-5. THE ROLE OF CFD IN ENGINE DESIGN

Historically, the quest for enhanced engine performance has led to the use of more complex engine configurations and more exotic materials. Even though computer usage has increased dramatically, the development test hours to achieve engine maturity have remained roughly constant. The ground test program is necessary to verify the safety, life and operational characteristics as well as the performance of the engine. Such demonstrations simply require time to accomplish, and any possible condensation is carefully considered in the existing development process. The history of engine testing shows that new tests have continued to be added, for example, tests for icing, water, sand and gun-gas ingestions, altitude relight, inlet distortion, thermal fatigue, rapid throttle movements, alternate fuels, and aeromechanics. Because of the obvious safety implications, necessary test facilities and techniques have been developed and built. It is reasonable to assume that the number of engine test hours will not be dramatically reduced in the next 15 to 20 years; progress in design capability will be used to enhance engine performance rather than reduce development time.

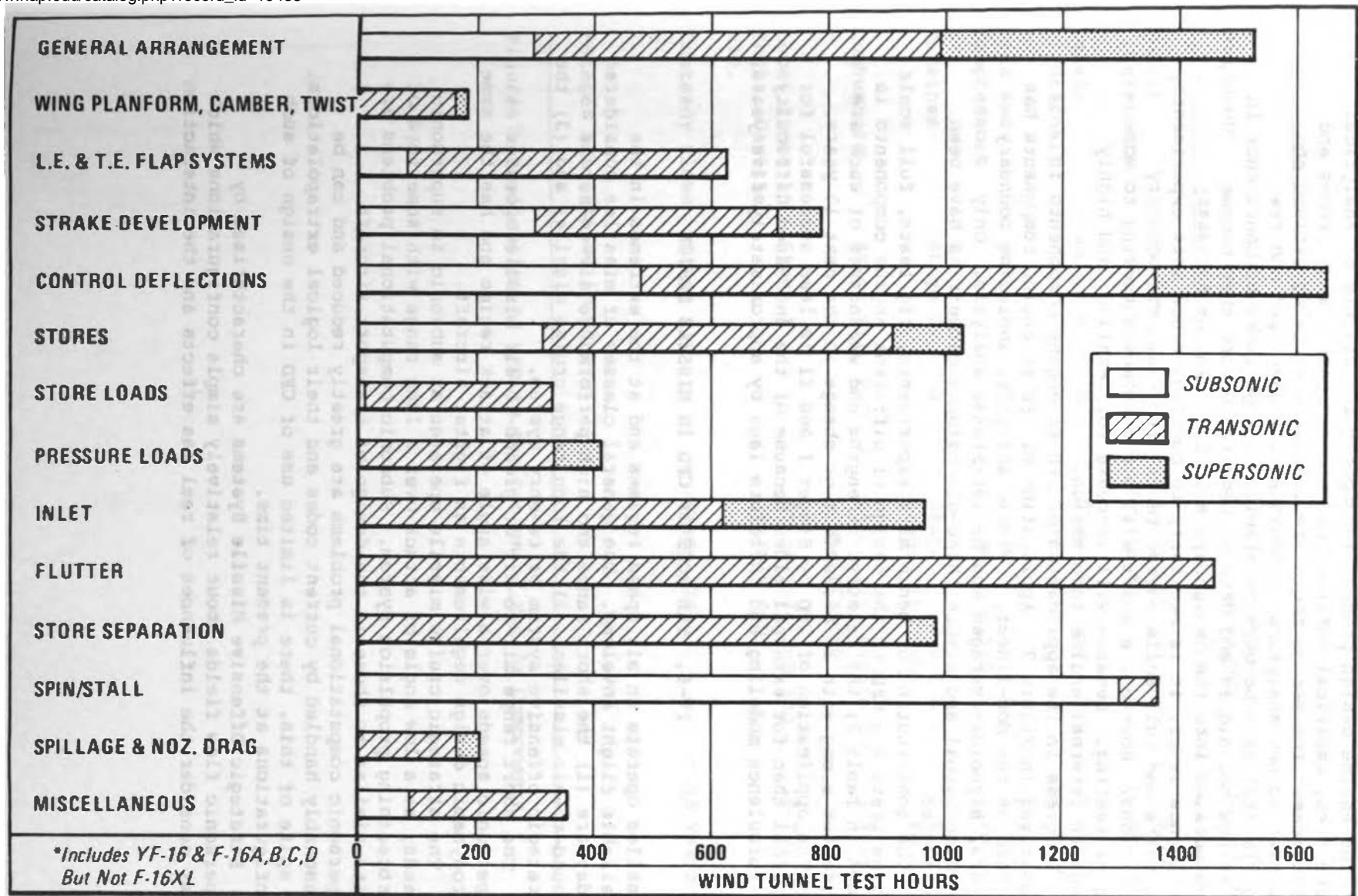


Figure 6 F-16 Wind Tunnel Test Summary (1971-1982).*

The engine design process incorporates a mixture of analytical techniques, empirical information, and designer's experiences and prejudices. The design tools are continuously being refined and improved as new analytical techniques are developed and new experimental data becomes available. A high level of confidence in these new techniques and data is required before they become incorporated into the design system. To build the necessary confidence level, it is necessary to continue bench mark experiments, rig tests and full scale engine tests with realistic boundary conditions. However, a shift will occur from rig testing to more engine testing. Demands will increase for detailed, and highly accurate internal engine information.

Progress in the application of CFD to engine components is summarized in Figure 7. Application of CFD to engine components has focused on the non-linear, inviscid analyses, including boundary layers, Reynolds-averaged and Navier-Stokes analysis. Only two-dimensional and simple three-dimensional geometries have been considered.

The contribution of bench mark experiments, rig tests, full scale engine tests and CFD to the design of different engine components is shown in Table 2; the relative strengths and weaknesses of each are presented along with an assessment of change in the next 15 years.

The application of CFD by Stages I and II is less successful for internal than for external flows because of the increased difficulty of turbulence modeling and therefore lags by approximately five years.

IV-6. THE ROLE OF CFD IN MISSILE DESIGN

Missiles operate in all speed regimes and at the extremes in the available flight envelope. The general classes of missiles considered today are (1) the short range and high performance air-to-air or ground-to-air missiles; (2) the long range cruise missile; and (3) the strategic offensive system or re-entry system.

The short range air-to-air or ground-to-air missile operates at supersonic speeds over a wide angle of attack regime and has the same aerodynamic design requirements as fighter aircraft.

The strategic cruise missile operates at subsonic to supersonic speeds, at a low angle of attack over a long range with some form of airbreathing propulsion system. Subsonic computational problems are quite similar to those in the design of transport aircraft. Supersonic computational problems are greatly reduced and can be reasonably handled by current codes and their logical extrapolations. In spite of this, there is limited use of CFD in the design of such configurations at the present time.

Strategic Offensive Missile Systems are characterized by hypersonic flow fields about relatively simple configurations which must consider the influences of real gas effects and the interaction

Component	CFD Capability in Hand	CFD Capability Under Development	Readiness for Design
Inlets (External)	Stage* II simple 3-D + B/L	Stage II, 3-D + B/L Stage III	5 Years 10 Years
Inlets (Internal)	Stage II, 2-D + B/L	Stage II, 3-D + B/L Stage III	5 Years 10 Years
Fans and Compressors	Stage II, 2-D	Stage II, 3-D + B/L Stage III, 3-D	5 Years 10 Years
Turbines	Stage II, 2-D	Stage II, 3-D + B/L Stage III, 3-D	5 Years 10 Years
Combustors	Stage III, 2-D	Stage III, Simple 3-D complete 3-D	5 Years
Local Flows in Seals, Cavities, Etc.	Stage I	Stage III, 2-D and Simple 3-D	10 Years
Unsteady Flows	Stage II	Stage III	15 Years

*Stages are defined in Chapter II

Figure 7 Application of CFD to the Design of Engine Components.

TABLE 2. RELATIVE STRENGTHS (AND WEAKNESSES) OF GROUND TESTING AND CFD ENGINE DESIGN

SUBJECT	GROUND TESTING	CFD	THE NEXT 15 YEARS
INLETS (Internal Aerodynamics)	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Provides information on all features of the interactive flow field, steady and unsteady. o Provides basic performance level information, including forces on the surface. o Compressor interactions can be included. o Surprises can be identified. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Accuracy of model tests is inadequate. o Difficult to extrapolate results to full scale Reynolds numbers. o Difficult to vary configurations. o Inadequate free stream simulation. 	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Allows external flow interactions to be modeled. o Provides initial information on prospective component performance. o Allows rapid sorting of effects of minor configuration changes. o Allows early identification of critical questions. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Many physical phenomena not now adequately modeled, including boundary layer control devices, unsteady effects, complicated geometries, compressor face interactions, etc. o Requires nonlinear inviscid or Reynolds-averaged Navier-Stokes computation for meaningful results. 	<p>-----CFD-----</p> <ul style="list-style-type: none"> o Ability to handle complicated duct geometries. o Ability to do 3D time-dependent, Reynolds-averaged, Navier-Stokes design computations for conventional and unusual geometries. <p>-----ground testing-----</p> <ul style="list-style-type: none"> o Reduction in routine performance testing. o More attention to localized phenomena and surprises.
NOZZLES	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Optimization of complex nozzles is more cost-effective with model tests. o Aerodynamic forces, cooling flows, and actuation can be included. o Surprises can be identified. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Scaling of model data to full size needs improvement. o Correction for external flow field effects is inadequate. 	<p>-----strengths-----</p> <ul style="list-style-type: none"> o CFD is used in the design of simple, non-separated nozzles <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Improvements in modeling flows is needed and must include: <ul style="list-style-type: none"> - cooling flows, - separation, - secondary flows in vectored nozzles. o Drag is not predicted. 	<p>-----CFD-----</p> <ul style="list-style-type: none"> o CFD analysis will be extended to include nozzles with separated flows. o Improvements will be made in modeling of flow in complex nozzles. <p>-----ground testing-----</p> <ul style="list-style-type: none"> o Dependence on nozzle testing will be reduced. o Test cells modified to improve external flow simulation.
FANS and COMPRESSORS	<p>-----strengths-----</p> <ul style="list-style-type: none"> o New concepts can be explored, e.g. influence of unsteady flow effects. o Surprises can be identified. o Design intent can be verified. o Performance within the selected geometry can be optimized. o Off-design performance can be measured. o Aeromechanical stability can be established. o Components can be developed for performance and durability. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Test costs are high. o Long turnaround time for hardware modifications. o There is little flexibility in optimizing the flow-path and physical geometry. o Accuracy and quantity of internal instrumentation is often inadequate. 	<p>-----strengths-----</p> <ul style="list-style-type: none"> o CFD is used routinely to design two-dimensional airfoil sections o Design of 3D passages is being initiated to optimize internal geometry selections. o Guidance from CFD is used to reduce development testing <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Loss (drag) prediction is inadequate o Flow modeling is inadequate to handle: <ul style="list-style-type: none"> - separation in complex geometry, - leakage flows, - large eddy simulation, - onset of flow instabilities. o Prediction of aero-mechanical stability is inadequate 	<p>-----CFD-----</p> <ul style="list-style-type: none"> o 3D flow analysis will be used for design. o Loss modeling will be improved. <p>-----ground testing-----</p> <ul style="list-style-type: none"> o Rig testing for performance will be reduced and replaced by expanded engine testing for life improvement. o Unobtrusive and accurate internal instrumentation will be developed.

TABLE 2. RELATIVE STRENGTHS (AND WEAKNESSES) OF GROUND TESTING AND CFD FOR ENGINE DESIGN

SUBJECT	GROUND TESTING	CFD	THE NEXT 15 YEARS
TURBINES (Aerodynamic considerations included in "FANS and COMPRESSORS" apply to turbines and are not repeated here.)	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Heat transfer coefficient information can be deduced. o Turbine cooling designs can be optimized. o Efficiency of cooled turbines can be measured. o Provides information for durability assessment. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Test cost is high. o Existing hardware limits flexibility for optimization. 	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Pressure distributions and boundary layer flows on airfoils and walls are predicted to allow estimates of heat transfer coefficients and optimization of cooling geometry selection. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Modeling of boundary layer flows, including transition and leading edge bubble separation and reattachment, is inadequate. o Modeling of cooling inside airfoils is inadequate. o Factor of 2 corrections have to be applied to reconcile predictions with experiments. 	<p>-----CFD-----</p> <ul style="list-style-type: none"> o Navier-Stokes, Reynolds-averaged analysis for transition, bubble separation and attachment will be developed for design. o Discrepancy between heat transfer prediction and data will be improved. <p>-----wind tunnel-----</p> <ul style="list-style-type: none"> o Some reduction in rig testing is expected. o Life testing in engines will not change.
COMBUSTORS	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Design intent can be verified. o Surprises can be identified. o Geometry can be optimized for flow uniformity, low emissions and combustor liner life. o Stability limits can be determined. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Test cost is high. o Existing hardware limits flexibility for geometry optimization. o Instrumentation accuracy and quantity is often inadequate. 	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Navier-Stokes, Reynolds-averaged analysis are being applied to identify attractive configurations. o Guidance from CFD is being used to reduce development testing. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Some physical phenomena are inadequately modeled: <ul style="list-style-type: none"> - mixing and combustion interaction, - flow with droplets and combustion, - combustor dynamics. 	<p>-----CFD-----</p> <ul style="list-style-type: none"> o Combustion related flow modeling will be improved and CFD used routinely in design. <p>-----ground testing-----</p> <ul style="list-style-type: none"> o Testing will continue to be needed to establish durability, performance and emissions. o Unobtrusive instrumentation will be developed.
LOCAL FLOWS and UNSTEADY FLOWS	<p>-----strengths-----</p> <ul style="list-style-type: none"> o Design intent can be verified. o Surprises can be identified. o Modifications to hardware can be identified to achieve design intent. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Extensive instrumentation and inspired diagnostic effort is required to identify problems. o Dedicated testing is too costly. 	<p>-----strengths-----</p> <ul style="list-style-type: none"> o CFD is being applied to predict the flows in cavities, seals and other parasites and to guide designers. o Guidance from CFD is used to reduce development testing. <p>-----weaknesses-----</p> <ul style="list-style-type: none"> o Major improvements in flow modeling are required to handle separated flows, unsteady flows, and flow instabilities. 	<p>-----CFD-----</p> <ul style="list-style-type: none"> o Major progress in the application of current CFD capability to the complex geometries, associated with the parasitic flows, is expected. o Little improvement in improving flow modeling is expected. <p>-----wind tunnel-----</p> <ul style="list-style-type: none"> o Testing is expected to continue.

of variable ablative surface contours with the aerodynamics of the configuration. Computational techniques are widely used in the design of these configurations both in the generation of data for design and in the extrapolation of wind tunnel data from the perfect gas ground test conditions to real gas flight applications.

V Facility Needs

V-1. USING CFD TO ENHANCE GROUND TEST FACILITY PERFORMANCE

The relationship of computers to ground test facilities seems to be one of growing interdependency. Although neither offers perfect answers to the questions of designers in the foreseeable future, each has advantages available for exploitation. On one hand, the computer promises relatively rapid, inexpensive CFD solutions, possibly including direct design optimization. On the other, the wind tunnel provides reasonable simulation of such complex phenomena as separated and vortex flows, and often is the first to reveal unexpected flow behavior. Designers will choose what they deem to be the "best" approach (not necessarily the cheapest) in each case. There is, and will continue to be, a balance between the computer and the wind tunnel.

An important benefit of computers in general and CFD in particular occurs when they are used to enhance the performance of ground test facilities. One way to appreciate this is to examine how computational capability can help the critical areas in experimental aerodynamic facilities that currently need improving. These can be grouped into three general categories, namely:

- A. Data quality--our ability to measure true data (e.g., lift, drag, thrust) to a high degree of accuracy.
- B. Operational efficiency--the means to control and reduce the cost of running major experimental facilities despite rapidly increasing labor and electrical energy costs.
- C. Simulation--the degree to which the facility faithfully reproduces the desired flight environment.

The general comments on each of these critical areas which follow below are equally applicable to wind tunnels and engine test facility performance enhancement. These comments are followed by specific examples from currently planned wind tunnel improvements. There are parallel developments in engine test techniques.

V-1-1. GENERAL EXAMPLES

A. Data Quality

Currently, CFD is employed during the pretest stage in order to identify problems of particular concern and their solutions. This includes the selection of model sizes, model support configurations, and flow conditions of greatest interest. The same calculations are applied during and after the testing phase in order to confirm the accuracy of the data, and occasionally to unravel unexpected results or explain discrepancies from model-to-model or facility-to-facility.

In the future, more powerful computers will make more of these capabilities available in the real-time, interactive mode of operation, and thereby increase the benefit of the present approach. Beyond this, we can look to CFD to provide the basis for the improved design of test cells, and more accurate post-test corrections for flow imperfections and model support systems.

B. Operational Efficiency

The amount of test time required to obtain a fixed quantity of data has already been greatly reduced via the computer by such direct means as on-line processing and displaying of raw and analyzed data, and programmed control of model and instrumentation attitude and position, as well as facility conditions. Cost reductions have also been obtained by controlling test conditions to constant aerodynamic parameters (e.g., coefficient of lift) rather than by interpolating within an extensive matrix.

The future will see a heavy impact of CFD upon the planning and operational philosophy of ground testing. We can anticipate a gradual change in test objectives towards only those regions where CFD is not sufficiently reliable.

Computers will also be essential to the dynamic operation of such facilities as the Aeropropulsion System Test Facility (ASTF), and ultimately may allow a specified amount of data to be obtained at the least cost or consuming the least energy.

C. Simulation

Ground testing currently employs a number of sophisticated, computer-based methods in order to improve the accuracy of simulation. Among these are pre-programmed controls which allow aircraft or engine models to be captively "flown" while dynamic data is obtained, and captive trajectory system testing, in which the model is maneuvered as it would in response to the forces it feels in "flight." The critical simulation problems today revolve about transonic and very high Reynolds' number flows. CFD is now used to extrapolate available data up to the correct Reynolds' number, as well as to compute flow properties that are hard to measure from those that are easier to obtain. In the future, CFD will enable the operation of transonic wind tunnels with walls which actively adapt their shape in

order to eliminate interference completely. CFD will also allow the design of substitute aircraft forebodies which provide the correct flow pattern for closely-coupled engine inlets within the narrow confines of the test facility.

V-1-2. SPECIFIC EXAMPLES

Several of the most important examples cited above are expanded upon below in order to more clearly illuminate the beneficial relationship between computers and ground testing.

Computer Model Control

Closed-loop model controls used in wind tunnel testing have been significantly improved in the past 15 years, and improvement is continuing. Computer and wind tunnel integration is mostly developed in the closed-loop control models, and this development has markedly influenced the integration of tunnel controls as well. The productivity of wind tunnels has increased remarkably at no loss in quality during this period and will probably continue to increase as closed-loop control of parameters is improved in both model and tunnel environments.

In addition to computer controlled angle-of-attack and sideslip programming, systems such as the Captive Aircraft Departure System (CADS) and Captive Trajectory Systems (CTS) represent very significant improvements in tunnel productivity. With the CADS the wind tunnel is used as an analog data source for the required static aerodynamic data and the Euler equations of motion for the aircraft are solved by an online digital computer. The solution of these equations is used to control the orientation of the model in the airstream. The CTS is an electromechanical six degree-of-freedom model support used for separation simulation. It provides aerodynamic coefficient data for online computer generation of the trajectory of a body as it is staged or separated from another body. The primary reason for dual or multibody testing is for simulation of flowfield interference on both primary and secondary bodies. The CTS is also used for computer controlled flowfield probe surveys and force/moment grid surveys of the secondary body in the presence of the first. These improvements provide increased productivity, added capability and improved data accuracy.

Computerized Tunnel Control

With the advent of the modern electronic computer it has become possible to automate numerous tunnel as well as model controls. With the increase in complexity of the aircraft under development, the control requirements placed upon the wind tunnel are accordingly increased. The free stream conditions must be maintained at precise and constant values. As suitable computing hardware and software

become available, more of the control features must be incorporated into a computer control system. The need for closed-loop automation of tunnel controls is clearly evident.

Computer control of ejector flaps, porosity, wall angle, drive speed to maintain constant pressures, temperatures, position, dynamic pressure, Mach number and Reynolds' number are required to insure test repeatability and reliability and have the added benefit of improving free stream flow quality. A more concerted emphasis needs to be made in the R&D of closed-loop controls as well as in the application of proven closed-loop techniques to upgrade existing facilities.

Tunnel Interference

Tunnel wall and flow quality can have uncertain influences on tunnel measurements. The true tunnel angle-of-attack is unknown because of wall interference effects, and the flight angle-of-attack is also unknown. Any numerical computations that are used to extrapolate tunnel test results must include corrections, however poorly understood, for wall interference flow quality. More research needs to be done to determine the influence of tunnel walls on flows about bodies and to obtain more understanding of the effect of Reynolds' number changes on flows of aerodynamic interest.

The adaptive wall will offer an opportunity to eliminate the large uncertainty due to the wall effect. It can improve that quality of test data by approximating "interference-free conditions" in a number of ways, among which are:

- Increased flow quality
- Absorption of the shock wave
- Blockage reduction (model and wake)
- Increased model-to-tunnel ratio (higher Reynolds' number)
- Improved model accuracy (resulting from larger model)

These conditions are attained using a computational fluid dynamics model to simulate the far field. Tunnel wall adjustments are made on the basis of the difference between the measured and computer parameters. The process is iterated until the tunnel conditions converge with those in the far field.

Advances in computational aerodynamics can provide existing low cost facilities with the capability of computationally determining tunnel wall effects without changing wall configurations by measuring pressure gradients at some distance from the model.

Mounting Systems

The demand for improved full-scale vehicle performance and accuracy of prediction requires an effort in the direction of improving test data accuracy from existing facilities. In addition, increase in tunnel costs has emphasized the need for improved

productivity without compromising accuracy. Wind tunnel facility improvements in the area of non-intrusive mounting systems will have to be developed to assure better full-scale representation of the models. The elimination or minimization of support system interference suggests new mounting systems such as the non-intrusive magnetic suspension being suggested by some researchers. Productivity improvements are also required in some existing facilities by incorporating model injection systems. Such systems currently being used in such facilities as the AEDC von Karman Facility (VKF) Tunnels A, B and C permit the model to be inserted into and removed from the test section without having to shut down the tunnel. The system is computer controlled and allows faster model configuration changes thus increasing tunnel productivity.

Measurement Systems

The demand for higher air vehicle performance is the driving force behind the need for more efficiency and increased simulation accuracy in wind tunnel testing. This is a trend that is gaining momentum and places a strain on current wind tunnel measurement systems. With improved techniques being developed to improve simulation quality, the need arises for new and improved data measurement systems. Non-intrusive instrumentation systems will require development, as well as flow visualization systems for the investigation of canard wakes as they interact with wing flowfields for the investigation of leading edge vortex flows, crossflow shock waves and the nature and extent of flow separation off the surface. Advanced flow visualization techniques and electro-optical measurement systems such as laser velocimeters, holographic interferometry, Moire pattern recognition and infrared scanning will be required for quantifying surface and off-surface conditions in aiding CFD validation. Quality, accuracy and repeatability of current instrumentation will require improvement as future aircraft performance requirements become more stringent.

Data Automation

An operating wind tunnel is capable of generating large quantities of raw data in a very short period of time. Systems to collect, reduce, display and analyze this data during wind tunnel operation will require continual improvement. An inefficient data acquisition/processing system generally requires longer-than-necessary tunnel testing. Recent decreasing cost trends of computer systems capable of supporting wind tunnel data systems and the increasing cost of electrical energy requirements for tunnel operation have combined to generate a strong economic inducement to increase wind tunnel efficiency through the incorporation of advanced data acquisition/processing systems in wind tunnels. The use of mini computers to perform pre-processing functions, data reduction, verification and formatting and micro-processors to support individual wind tunnel instruments has proved to be very cost-effective in

relieving the central computer of overly complex software and processing requirements. The use of interactive terminals within wind tunnel data systems has great potential for more productive testing of models. Technology breakthroughs in recent years have made "smart" terminals available along with color CRT's (cathode ray tube) and very sophisticated graphics software and hardware systems. On line data analysis offers the potential for further economies by early identification of areas requiring more detailed investigation.

Math model validation systems will be required in wind tunnels as design by analysis becomes more commonplace. State-of-the-art computers will be needed at the tunnel testing site to be used for math model verification during tunnel tests. With a computer-integrated wind tunnel, both the validation and application of a computational code will result in a reduction in the number of tunnel entries, a decrease in required run time, and a significant cost savings.

V-2. NEW FACILITY REQUIREMENTS AS INFLUENCED BY CFD

V-2-1. TEST FACILITIES AS VERIFICATION OF CFD TECHNIQUES

It is clear from preceding chapters that for the next 15 years test facility results will be required for establishment of confidence in CFD methods of aerodynamic design. It is appropriate to inquire whether the present facilities will be adequate for this task. In fact, verification of CFD Stage III methods (Reynolds-averaged Navier-Stokes) depends completely upon accurate representation of boundary layer conditions at flight Reynolds' numbers and the currently operating wind tunnels cannot supply this information. Fortunately, the NASA National Transonic Facility (NTF) will soon be operational and for much of the 15-year period it will provide experimental data at high Reynolds' numbers for CFD verification.

With this exception, CFD developments can for the most part be supported by experimental verification in existing facilities. There is a requirement for instrumentation capable of exploring the complete field and in particular the off-surface flow conditions. As discussed in the preceding section, this requirement can be satisfied by the advanced flow visualization techniques now becoming available.

V-2-2. NEW DESIGN CONCEPTS AND THEIR FACILITY REQUIREMENTS

Aircraft

New aircraft programs within the next 15 years will require an expanded flight envelope, particularly in angle-of-attack and yaw. Few current wind tunnels can accommodate this requirement without drastic decrease in model size and the analytic representation of the flow by CFD methods will strain the capability of Stage III methods. The modified 80' X 120' full scale tunnel at NASA Ames Research Center

with suitable instrumentation may alleviate this difficulty. Furthermore, at higher speeds the NTF may be able to provide data at high angle-of-attack since small models can be used without severely compromising Reynolds' number. A similar situation exists in regard to vertical and short takeoff and landing vehicles (V/STOL) testing and the verification of CFD approaches to V/STOL. A vertical and transitional (vertical to horizontal) flight test capability is desirable. It appears neither method, CFD nor wind tunnels, will be adequate within the period being considered.

Engines

The engines which will require ground test within the next 15 years are not commitments but many are currently under study. Table 3 lists these classes of engines and their potential features.

TABLE 3 Potential Engine Requirements to Year 2000

APPLICATION	ENGINE SIZE THRUST OR HORSEPOWER	ENGINE CONFIGURATION	SPECIAL FEATURES
Tactical Fighter	20,000-30,000 lbs.	Augmented turbofan or turbojet	Novel airframe installations
V/STOL	20,000-40,000 lbs. 20,000-25,000 lbs.	Augmented turbojet Augmented turbofan	Thrust reversing Thrust vectoring
Bomber	30,000-40,000 lbs.	Augmented Turbofan	Stealth
Patrol	5,000-10,000 shp.	Turboprop	Low speed aircraft
Transport/ Airlift	20,000-50,000 lbs.	High bypass turbofan	
Commercial Transport	up to 70,000 lbs.	High bypass turbofan	Extreme premium on fuel efficiency
Commuter Transport	10,000-15,000 shp.	Turboprop	Quiet high speed subsonic aircraft with up to 15 ft. diameter pro- pellers

Small engines have been excluded from this assessment since they are unlikely to tax the capabilities of major facilities.

It is reasonable to expect that derivatives of existing engines will be developed and that new engines will be designed to meet the potential requirements. These new engine configurations will require special facility features to handle the following:

- o testing of engine/inlet combinations at high angles-of-attack to ensure stability throughout the flight envelope (enhanced ASTF capability)
- o radically new airframe configurations with demanding engine installations
- o thrust vectoring
- o turboshaft engine testing (a large dynamometer will be required)
- o evaluation of the interaction of the propeller flow with the aircraft.

Ground testing of larger and more powerful engines, and the integrated performance of engine/airframes will be possible when AEDC's Aeropropulsion Systems Test Facility (ASTF) is completed and becomes operational.

Since, in general, the test programs represented by the above requirements combine aerodynamic measurement and verifications of the life, transient response, and emissions aspects of the new concept, it is not expected that CFD developments in the interim will reduce the necessity for experimental facilities.

Possible Decrease in Facility Use

The experimental laboratories of the country are continually examining the capability of their facilities in relation to their future demand in order to assess both the need for new facilities and future work load. It is particularly difficult to assess the probability of diminished demand as a result of CFD techniques because one cannot readily assess the date at which the designer will proceed with confidence in CFD without verification by experimental data. This might be estimated based on user views expressed in Chapter IV. For example, it appears probable that the hypersonic reentry vehicle, which already depends more than any other flow regime on design by analytical methods to account for the effects of real gas flows, will arrive at full CFD application and confidence at an early stage. In contrast, it appears that full utilization of CFD techniques will occur much later for tactical aircraft design and the same holds true for engine testing in general.

Across the board, the specific time in which independence of experimental verification will occur is dependent upon the confidence of the designer and his ability to adequately design and build the product without a significant probability of error.

VI

Conclusion—Acceptance of CFD as a Design Tool

CFD is already a powerful tool and its strength will increase significantly in the next five to ten years to the point where it can be a very important aircraft and engine design tool; however, the extensive application of CFD hinges upon two major considerations. First, the designer must have a high degree of confidence in the computational methods for aerodynamic design. Second, management from industry and government must believe that CFD can permit a quicker, more economical system development to a given level of excellence than could be achieved using experimental test facilities.

Designer confidence stems from accumulated experience in applying the CFD methods to specific design problems with accurate results. This confidence can be gained in the later stages of Phase II and in Phase III of the Development Cycle for Major Computational Capability (Figure 4 of Chapter IV). In order for the designer to make use of the CFD capability he must have access to user-friendly codes that can be readily applied to the real geometric constraints of his configuration. Further, the designer has to be assured that the accuracy of the computational results has been proven for his specific application. This assurance can only come from careful verification of the method by comparison with detailed test data from wind tunnel and/or flight tests.

Once the aircraft designers are willing to use the computational capability, both industry and government management must have confidence in the accuracy and utility of CFD as a design tool. Management acceptance is, perhaps, the most important factor in determining the extent to which computational methods are applied to the detailed design of aircraft. Management acceptance is frequently lacking at the present, especially for high performance military aircraft where extreme viscous and vortical flow fields dominate the aerodynamic design.

The aircraft industry must behave in a conservative way, because it is governed by stringent performance guarantees on its products. Management acceptance of new computational design tools will only result from application of the codes to complex design problems over a long period of time with parallel experimental testing for verification

at all levels of the flight spectrum. This management confidence building is an important part of Phase III of the Development Cycle for Major Computational Capability (see Fig. 4, Chapter IV).

As an example, one can draw on the experience of the commercial aircraft industry where computational capability for fully-attached flow has been developed to a high degree over the past 15 to 20 years. While computational design capability has certainly contributed measurably to improve the commercial aircraft designs, there is no evidence of large reductions in wind tunnel testing in the latest generation of aircraft. We are, in fact, still at the phase where strengthening of confidence in the CFD result is considered desirable.

Of course, the anticipated explosive advances in computer hardware coupled with accelerated development of CFD software to solve more complex flow fields will provide a strong catalyst to speed up design application. Nevertheless, full management confidence in CFD and belief in its capability as the primary design tool will take most, if not all, of the next 15 years.

The above comments on the need for management confidence apply equally to the acceptance of CFD discussed above in Chapter V, "CFD for Wind Tunnel Enhancement." In order to make the best use of CFD in test facilities it is necessary for the facility management and the government or commercial agency to which it belongs to recognize the strength of CFD techniques and their value if applied to current facilities.

Appendixes

APPENDIX A

Memorandum of Understanding
Between
Arnold Engineering Development Center (AFSC)
and
Office of Aeronautics and Space Technology (NASA)
Concerning
An ASEB Study of Computational Aerodynamics
Simulation Technology Developments



Brig. Gen. Michael H. Alexander
Commander, Arnold Engineering
Development Center



Jack L. Kerrebrock
Associate Administrator for
Aeronautics and Space Technology

Date 12/1/81

Date 11/16/81

Introduction

The National Academy of Sciences, through its Aeronautics and Space Engineering Board, proposes to establish a committee to study computational aerodynamics simulation technology developments. This study will be conducted by a 10-member committee selected in accordance with National Research Council procedures. The study will be conducted over a 12-month period at an estimated cost of \$123,000.

Advanced computer technology, combined with lower cost and higher capacity memory technology, represents a desirable capability for obtaining both open and closed form solutions of the Navier-Stokes equations for viscous flow in the presence of moderate pressure gradients. These technology developments promise to provide economical techniques for analytical and experimental evaluation of environmental effects on atmospheric flight and propulsion systems. They offer the possibility of acquiring data that are free of facility interference effects, turbulence, flow quality, Reynolds number, and other well known error sources. On the other hand, ground test facilities will still be required to verify the accuracy of computer codes or to prove the reliability of propulsion and aerodynamic systems prior to flight. The study will examine long term capabilities of computational analysis techniques and the cost trends associated with future capabilities and compare them with projected development facility costs and capabilities. The Arnold Engineering Development Center (AEDC) and the Office of Aeronautics and Space Technology (OAST) will share equally the funding of this study. The study will be conducted as a task under OAST's master agreement with the Aeronautics and Space Engineering Board of the National Research Council.

Purpose

The objective of the study will be to determine the impact of developments in computational fluid dynamics technology on the traditional role of conventional aeronautical ground development facilities. Changes in testing programs and procedures resulting from advancing computational fluid dynamics technology are likely to be significant in the coming decade. Timely information is needed by the AEDC of future impacts of computational fluid dynamics technology as a basis for decisions regarding utilization, modifications, closings, or new construction of aeronautical ground development facilities.

Study Funding

The cost of the study will be shared equally between the AEDC and OAST. The AEDC will provide its share to OAST which will act as the procurement office for the joint study.

Procurement Policy

The study will be conducted under NASA policy, regulations and procedures except where specific statutory requirements of AEDC require otherwise. The study will be a task arrangement under the OAST master agreement with the Aeronautics and Space Engineering Board of the National Research Council.

Management Policy

The study will be monitored jointly by designated personnel representing the AEDC and OAST. Any changes or modifications to the study will be mutually agreeable to both parties, however, technical liaison with the ASEB will be the sole responsibility of NASA.

Scope of Study

- o Examine predicted changes in computer storage and processing capabilities and associated cost trends applicable to internal and external aerodynamic flow simulations during the next 15 years;
- o Interpret such trend data in terms of approximate cost to solve design and development problems and then compare them with the anticipated cost of using ground development facilities to obtain similar results;
- o Identify classes of design problems that are better handled either by computational fluid dynamics or by ground development facilities;
- o Identify, in particular, types of problems that are not likely to be handled adequately by computational fluid dynamics and for which a satisfactory ground development capability does not exist; and
- o Review the long range plans of the AEDC in light of the trends and problems identified by the committee and emphasizing the types of ground development facilities used at the Center.

It is anticipated that the study will provide information that will permit the AEDC planning personnel to evaluate which ground development facilities are likely to see decreased workloads, which will remain essentially unchanged, and which could benefit from modification to meet the challenges and opportunities presented by computational fluid dynamics during the next 15 years.

The study committee will consist of experts in computational mechanics and experimental facilities technology, and in the underlying sciences as well as the application of the technology.

Study Plan

The committee will conduct its work in accordance with the following tentative schedule of activities:

- o Following contract approval, approximately eight weeks will be required to complete the selection and appointment of the chairman and members of the committee, develop a detailed work plan and complete arrangements for the first meeting;
- o A 2-day meeting to review pertinent background information, define problems and issues, and agree on study approach;
- o A 6-week period to assemble and examine use and cost data and trends relevant to both computational simulation and ground testing methods;
- o A 10-week period devoted primarily to (a) drafting of a comparative analysis of the two methods including, in particular, consideration of the issue regarding proper balance in utilizing the optimum capabilities of each technology, and (b) completing arrangements for the second meeting;
- o A 2-day committee meeting to (a) discuss the analytical comparison of the two methods and the implications of the findings relative to the purposes described in the above plan of action, and (b) develop coordinated recommendations;
- o A 12-week period to (a) develop a draft of the final report and to obtain and incorporate comments from committee members, and (b) complete arrangements for third meeting;
- o A 2-day meeting to discuss and agree on the substance, conclusions, and recommendations of the final report; and
- o A 12-week period to complete the Academy report review process prior to report distribution.

The Aeronautics and Space Engineering Board will assume overall cognizant responsibility for the study, including review of proposed committee membership, study plans, milestones, and conclusions and recommendations developed by the committee.

As appropriate, the AEDC and OAST will provide to the committee information on its relevant plans and programs and its representatives will be available to the committee for consultations and briefings. Additional information of a similar nature will be obtained from other activities as necessary.

APPENDIX B

MICROELECTRONICS AND THE SUPERCOMPUTER INDUSTRY THROUGH 1995

By Sidney Fernbach

The projections by Dean Chapman (Ref. 1) regarding the development of computers as shown in Figures 1 and 2 can be expected to hold true through the 1990s. Even the more optimistic Japanese make no claim for a replacement for silicon before the 1990s. Using silicon technology then, we will have to depend on architectural designs for major gains in performance. In the case of the CRAY-2 for example, there is a multiprocessor system with 4 CPUs, in the case of the CDC 2XX, presumably an eight-pipe system, and if Burroughs remains in the picture, a 512 processor system.

Memory size will increase since we shall achieve 1M bit chips by 1995. Even back-up disk memory and archival storage will show substantial improvements now that we realize the potential of vertical magnetic as well as optical recording.

Costs of hardware will increase only because we will be asking for more--more logic, more memory, and probably more processors in a single system. Cost of software will increase tremendously. We have not learned to write large system in a well structured way or with computer aided software design. Now that we are expecting vector and multiprocessing systems to proliferate we should be spending more time and effort studying optimization techniques than we are.

The cost of the software for the STAR 100 system was roughly \$20M. Rough estimates by Cray Research indicate expenditures to date on CRAY-1 of \$15-25M. Cyber 205 software costs are running at about \$4M per year. This is the fourth year and there are more to come. The 2XX, as a complete system, will cost more.

Assuming then that we will be considering only silicon technology until 1995, the following sections review what we may expect until then in components, computers, peripherals, software and systems.

COMPONENT TECHNOLOGY

A silicon metal oxide semiconductor (MOS) memory of 1 Megabit storage content will be introduced in the mid-1980s, a 4 Megabit memory, by 1990. It usually takes about 3 years to put these into production. Equivalent sized bipolar memories will follow within 3 to 5 years

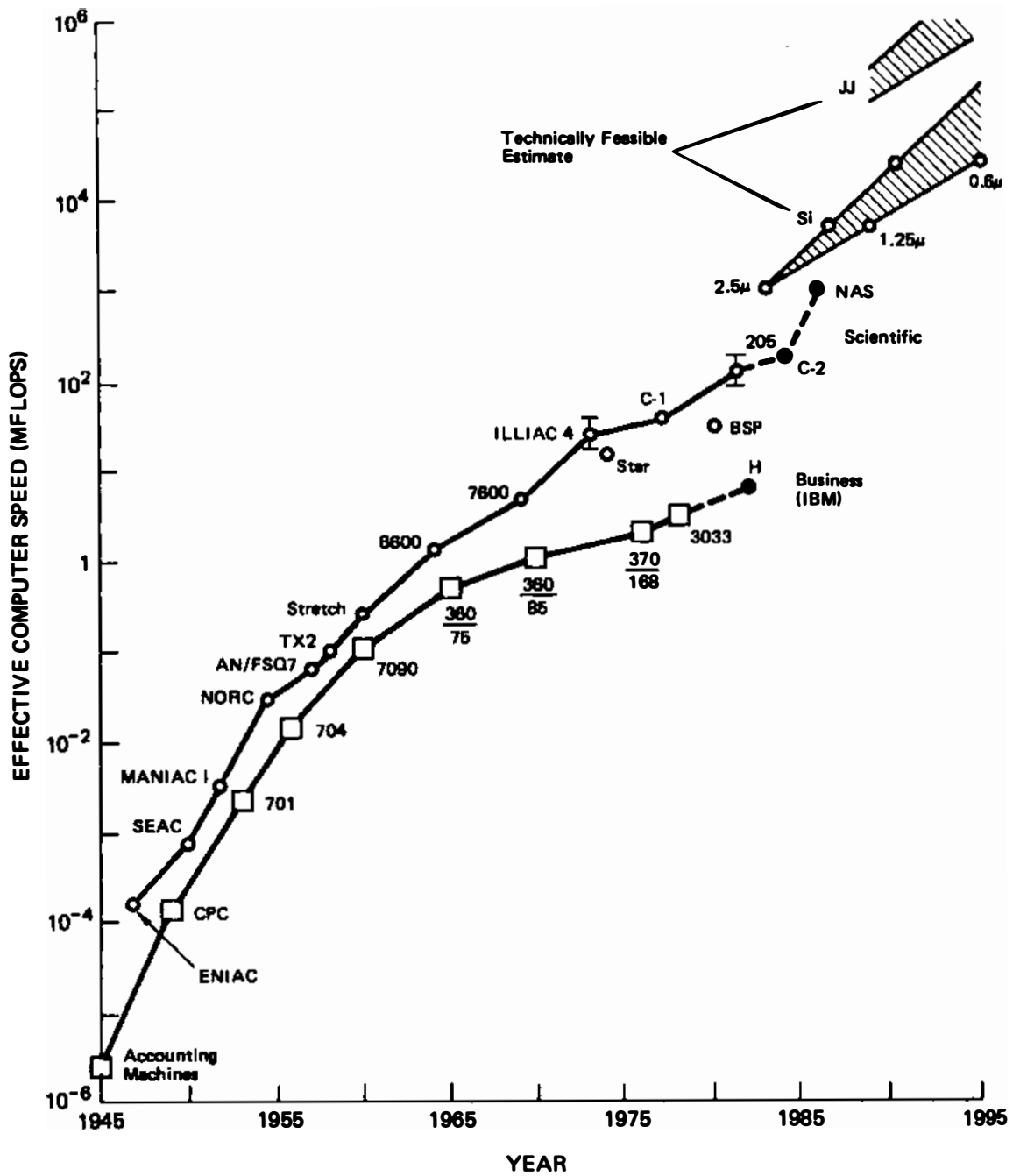


Figure 1 Development of Supercomputers - Computer Speed.
(Dean Chapman)

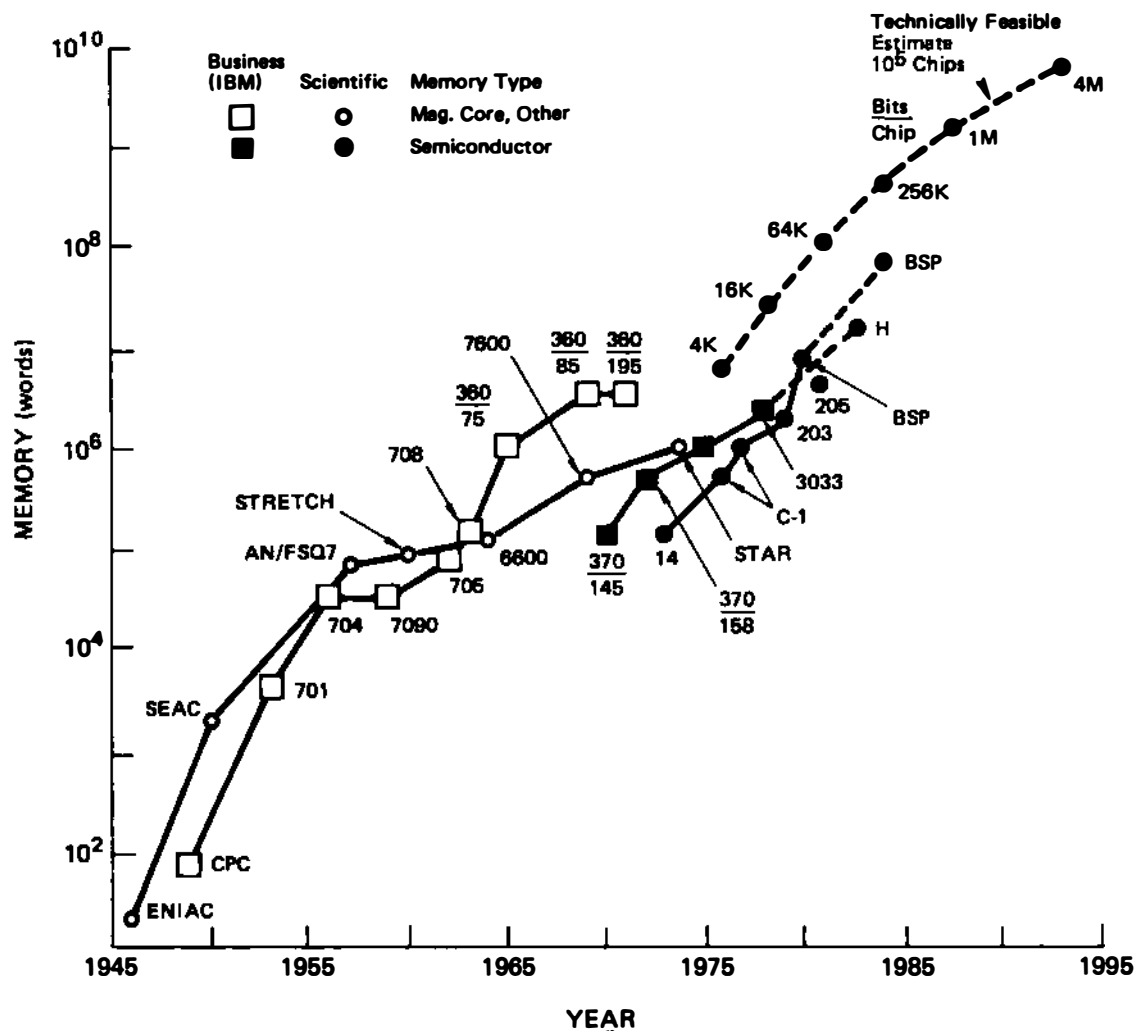


Figure 2 Development of Supercomputers - Memory Size.
 (Dean Chapman)

after the MOS introduction (Figure 3). A comparison of content trend of magnetic bubble, MOS random access memory and bipolar logic vs. introduction times is shown in Figure 4. By 1995 we should be implementing the following single chips for large scale computers.

- o 64 Megabit magnetic bubble memory
- o 4 Megabit MOS RWM
- o 16 bit MOS microprocessor/246kb memory
- o 10^5 gate bipolar logic circuits

Figure 5 shows storage capacity as a function of linewidth for the minimum case which is physically achievable (but expensive) and the optimum case which is most likely to predominate. The minimum practical linewidth is of the order of 0.7 microns. It is interesting that phase two of the Very High Speed Integrated Circuit (VHSIC) program aims at 0.5 microns by 1987, but will be satisfied with 0.8 microns. The trends of linewidth with date of introduction are shown in Figure 6. It has to be pointed out that these dates would hold only if the manufacturer aims at the minimum figure. If he aims at the optimum figure instead, there will be a delay in the introduction of the smaller linewidths. Along with the decreasing linewidth comes a change in chip areas. If we follow the minimum linewidth curve, the circuit area should decrease; if not, the chip area will increase.

As the state of the art advances, it is expected that more complex Very Large Scale Integration (VLSI) systems will consist of several multifunction chips and eventually of larger monolithic systems. The number of packages per system will decrease, the cost of fabrication per chip will increase slightly with the end result that cost per average system will continue to decline.

Despite increasing reliability at the component level, mean-time to failure at circuit (or system) level will decrease. This is because the mean-time to failure at the lead, circuit, or system level will show a slight decreasing trend. This is shown in Figure 7.

The smallest linewidths that can be achieved economically in a production environment will level off at about 0.7 microns. Some special circuits may achieve 0.2 microns. Oxide and insulator thickness on the order of $5\mu\text{m}$ will become widespread. Impurity depths of 0.1 microns will be the lower limit. The lowest impurity density will have to go to 10^{17}cm^{-3} (from 10^{15}). Operating voltages may go from 5v to 1v (lower voltages being impractical--approaching noise level). The switching energy per bit will level off at 10^{-4}pJ/bit as a result of load requirements, but lines and other interconnections. Chip area (now $\sim 1\text{cm}^2$) will ultimately increase to 100 cm^2 with storage densities of 10^7 bits/cm^2 ($10\text{ microns}^2/\text{bit}$) (Table 1). At the turn of the century a monolithic 16Mb silicon memory will be introduced. Quadrupling thereafter will take place every decade instead of every 4 years. Gallium arsenide (GaAs) and bubble memories will assume prominent roles. Silicon will continue to be most promising semiconductor material useful for VLSI circuits.

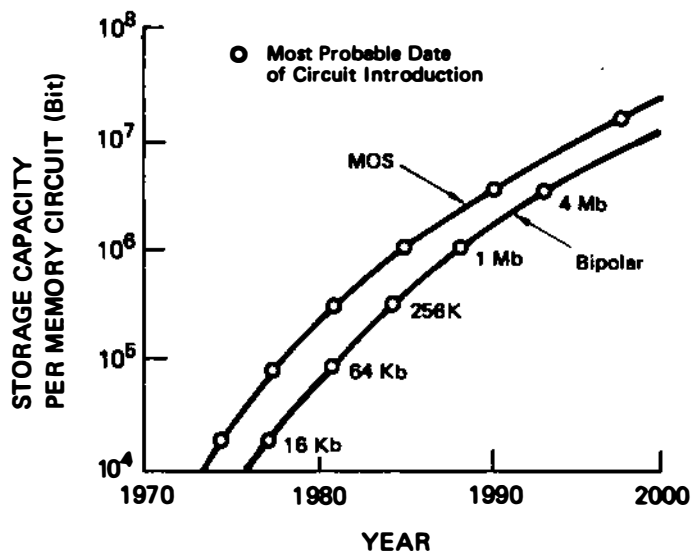


Figure 3 Most Probable Trends of Storage Capacities of MOS and Bipolar Memories (Silicon), Defined by Circuit Introduction Times. (Courtesy of Gnostic Concepts)

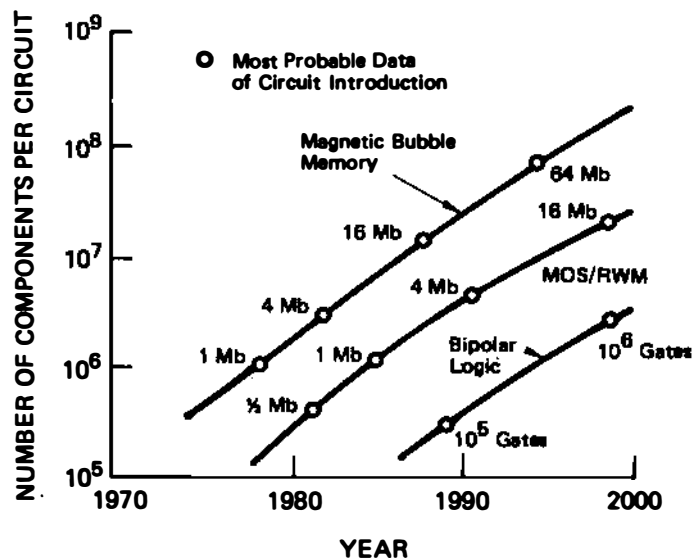


Figure 4 Expected Trends of Component Content Per VLSI Circuit, Assuming Single Function Chips. (Courtesy of Gnostic Concepts)

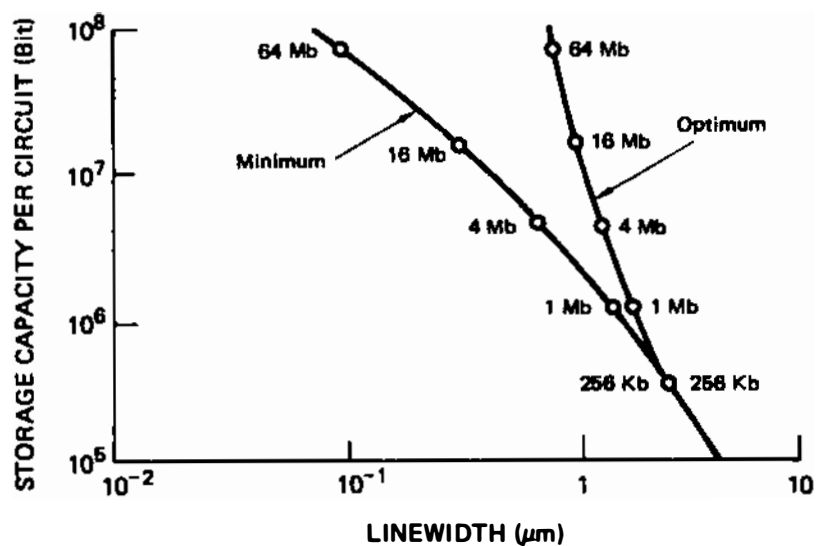


Figure 5 Relationship Between Linewidth and Storage Capacity in MOS VLSI Circuits Under Optimum and Minimum Conditions.

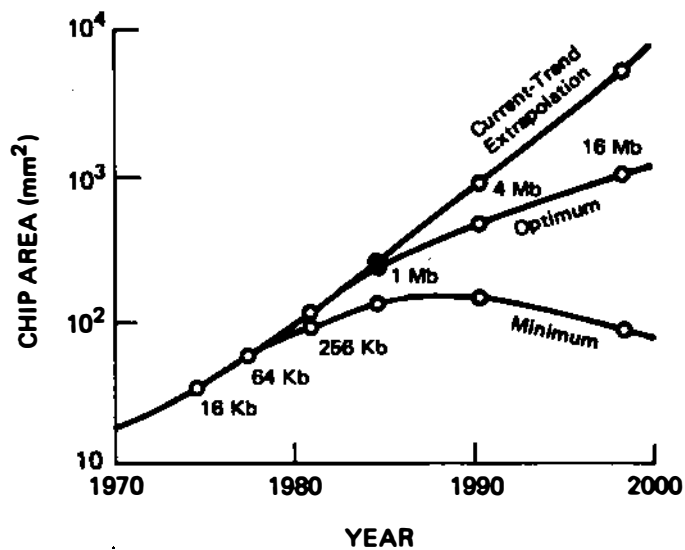
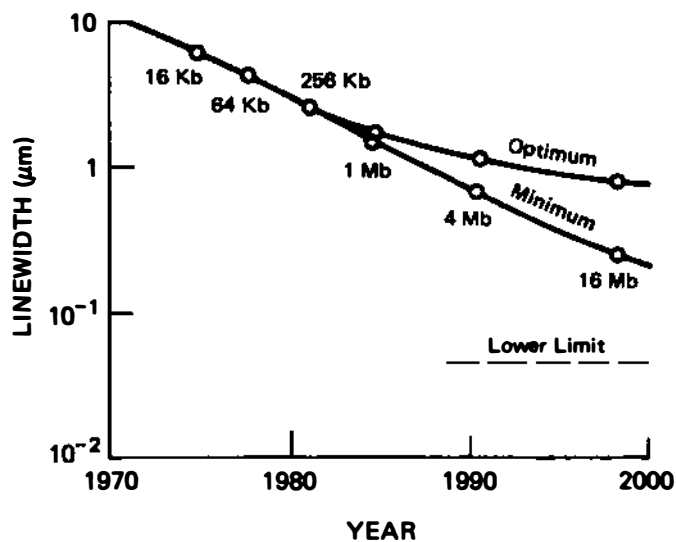


Figure 6 Trends of the Linewidth and Area Requirements of MOS/RWM Circuits at Time of Introduction.

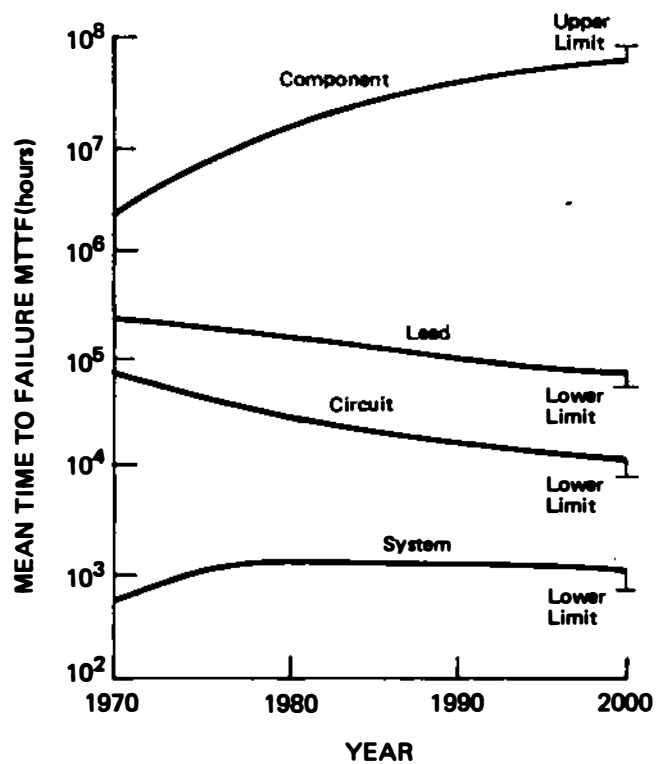


Figure 7 Estimated Variation of Mean Time to Failure with Time Given for VLSI Circuit and System and Compared to Circuit Component and Package Lead (MOS Memories at Time of Introduction).

TABLE 1 Typical Properties of State of the Art VLSI MOS Circuits

CHARACTERISTIC	1975	1985	ULTIMATE
Lateral Dimension (μm)	4.0	1.0	0.5
Vertical Dimension (μm)			
Doped Layer	2.0	1.0	0.1
Insulating Layer	0.1	0.02	0.005
Impurity Density (cm^{-3})	10^{15}	10^{16}	10^{17}
Operating Voltage (V)	5.0	2.5	1.0
Switching Energy (pJ/Bit)	10	10^{-1}	10^{-4}
Maximum Chip Area (mm^2)	100	500	10,000
Maximum Bit Areas (μm^2)	10^4	10^3	10
Storage Density (Bits/mm^2)	10^4	10^5	10^7

The estimates above were made by Gnostic Concepts several years ago and may be optimistic. More recent and perhaps more realistic numbers obtained early in 1982 show a lag of 4 to 6 years in some of these developments (Figures 8 and 9). In Figure 8, ECL stands for Electron Current Logic, which represents the highest level of technology for performance.

Enhanced circuit complexity will lead to generations of monolithic systems whose character is mainly determined by changes in software rather than changes in hardware. Because of the substantial investments in design, development and testing, as well as in the fabrication equipment of the large circuits and systems, these circuits and systems will be contemplated only if there is promise of a large market to recover the initial investment. This will force the development of a few universal types that can be used regardless of application and where individuality is determined by software. Thus, the semiconductor industry will undergo a transformation from integrated circuit to integrated systems with a shift emphasis from hardware changes to software changes and with fewer, but standardized, circuit types.

Despite the efforts of IBM in Josephson Junction (JJ) technology and the Japanese and others in both JJ and GaAs technology, there is continuing belief that silicon technology will be most suitable for most VLSI circuits through the 1990s. GaAs offers some promise, mainly because of its higher carrier velocity, but its fabrication characteristics do not allow a cost efficient manufacturing of VLSI circuits, partially because of inferior mechanical properties and the need for deposited oxides.

It is hard to find analysts who project prices out more than 5 years. The statement that prices of memory are decreasing 25 to 30 percent per year until the 1M bit chip is manufactured seems acceptable. An illustration of a projection on the 64K MOS dynamic RAM is shown in Figure 10(a). The 256K chip should be coming in before this cycle is completed. The worldwide shipment of 1K, 4K, and 16K RAMS is shown in 10(b), and the peaking of the 64K towards 1986 in 10(c). As yet there are no projections on the 256K RAM.

One must also realize that these MOS memory chips are not often used in supercomputers, that they are less expensive than bipolar memory, and they appear on the market a number of years earlier than bipolar of equivalent density. See Figures 8 and 9 for comparative data. Pricing data is difficult to obtain.

CURRENT AND PLANNED SUPERCOMPUTERS

The supercomputer era was begun in the 1970s with the delivery of CDC's STAR 100, the Texas Instruments Advanced Scientific Computer (ASC), and Burroughs Illiac IV. Only the CDC line of equipment (along with the ensuing CRAY line) is shown in Figure 11 which shows the family developments through 1990. STAR 100 was typical of the three "experimental" machines of that day. Both it and the ASC were highly pipelined to gain effective speed on long vectors. Short vectors and

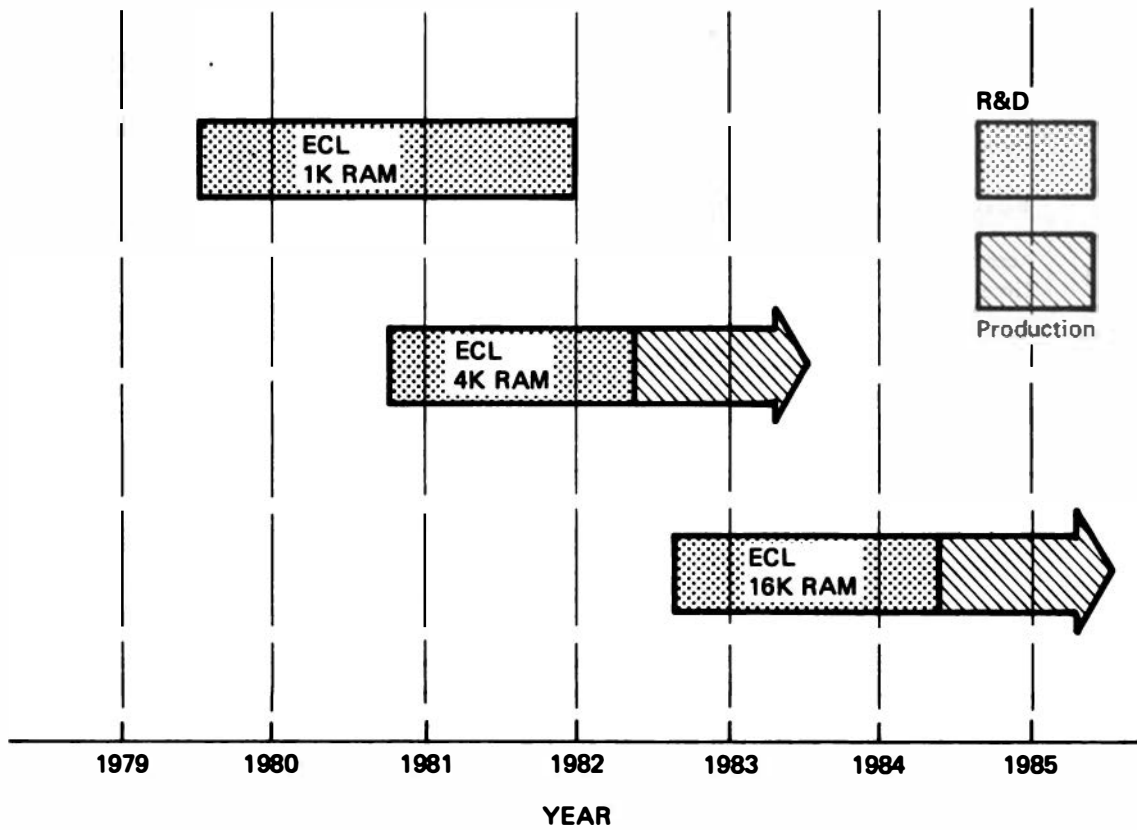


Figure 8 Semiconductor Technology
High Performance Main Memory Roadmap ($\leq 50\text{ns } t_{\text{acc}}$).
(Courtesy of Control Data Corporation, 1982)

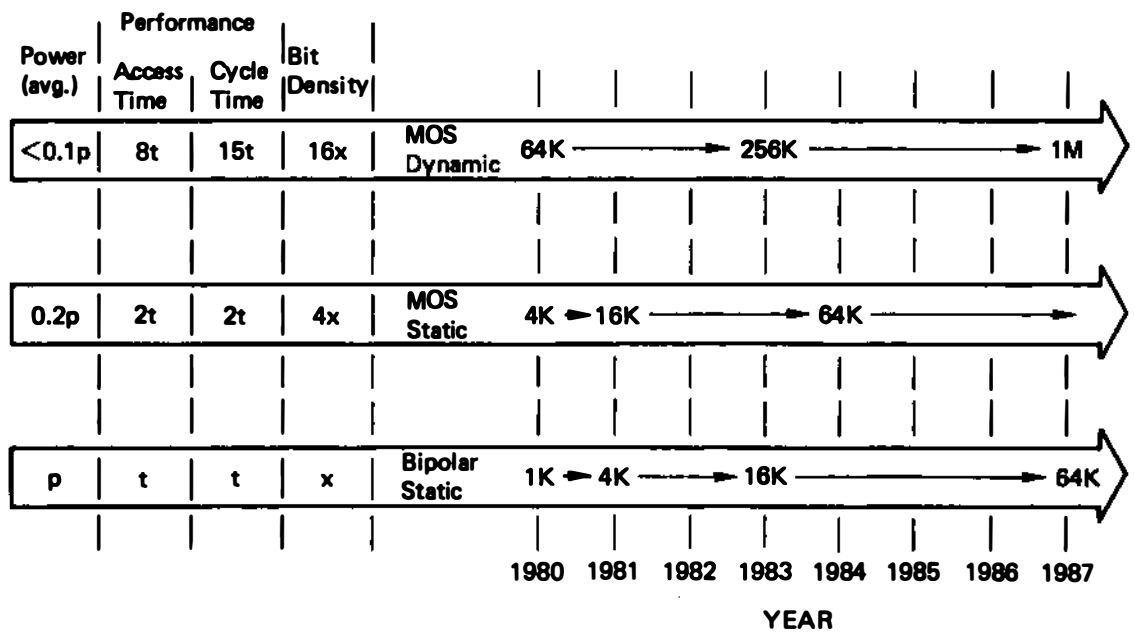


Figure 9 Relative Density/Performance Trends for Storage Technology. (Courtesy of Control Data Corporation, 1982)

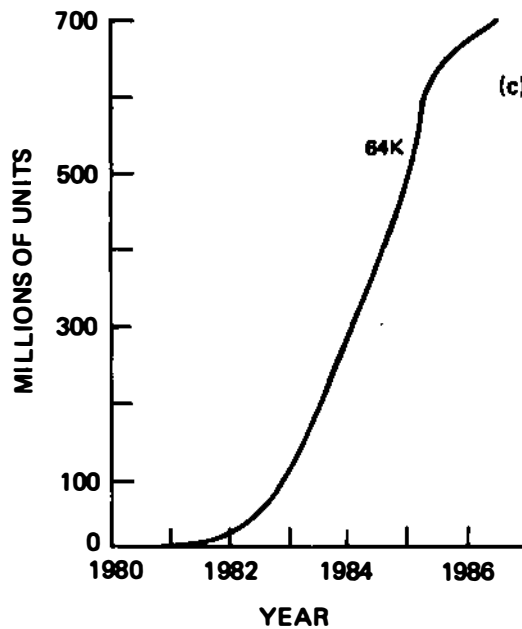
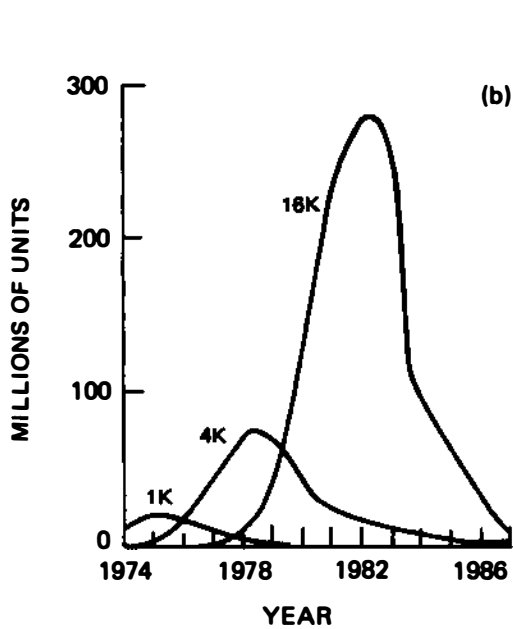
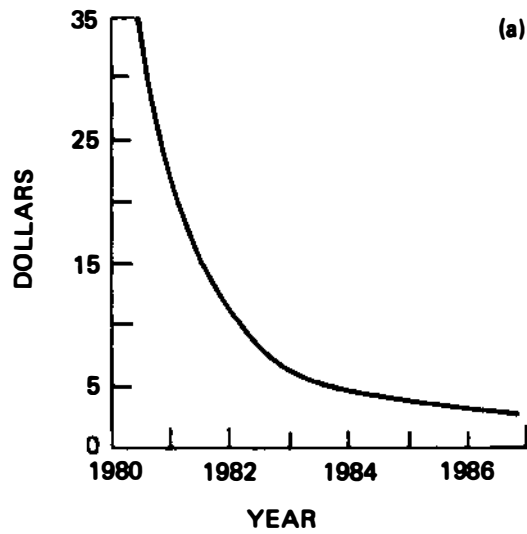


Figure 10 Estimated World Wide Shipments and Selling Price of Dynamic RAMS (Courtesy of DATAQUEST, Inc., May 1981)

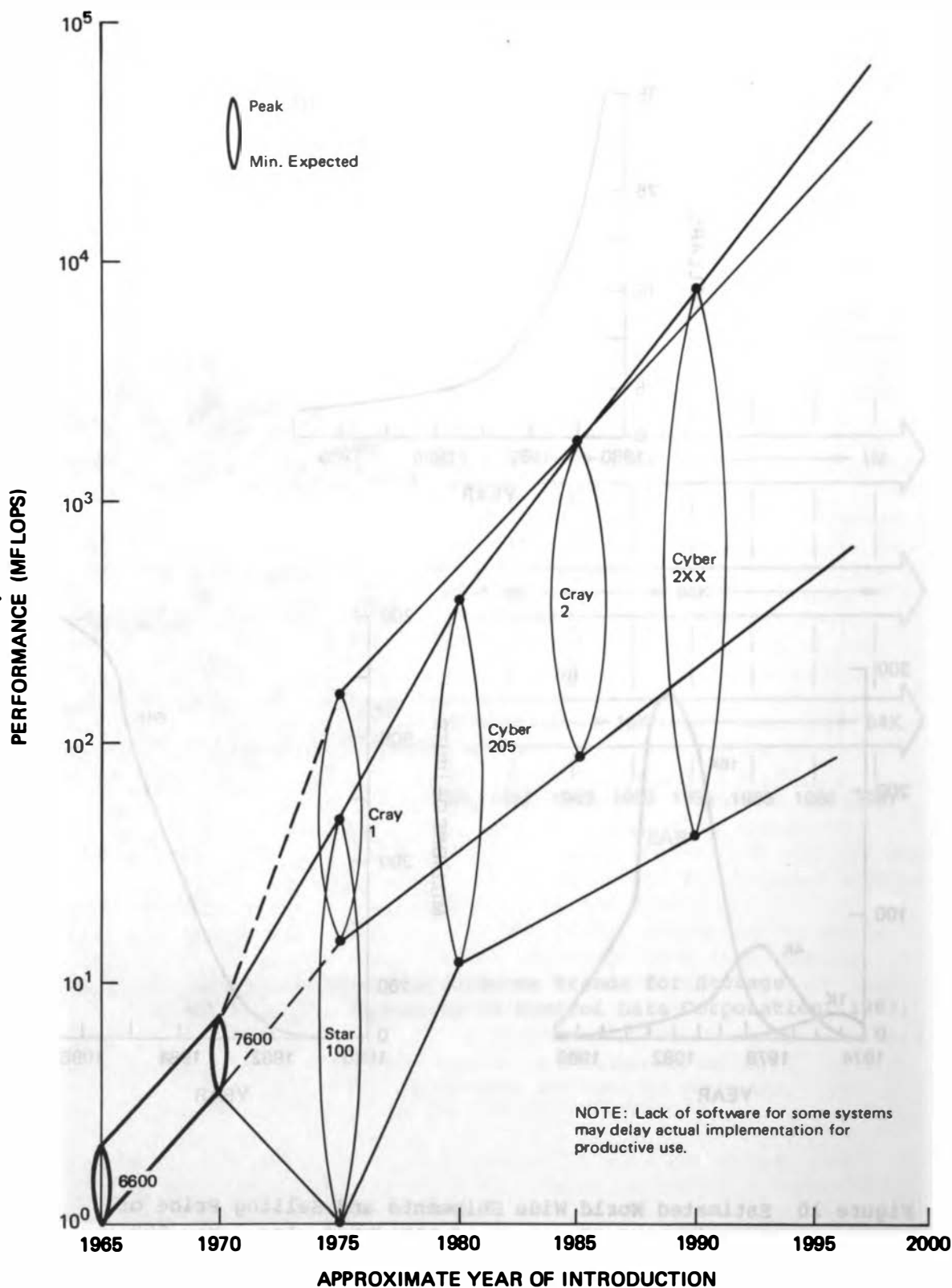


Figure 11 Performance of CDC and CRAY High-end Computers Actual and Anticipated Through 1990. (For 60/64 bit arithmetic)

scalars were not considered important, although it was just that, along with hardware reliability problems (especially in STAR 100) that gave these systems a poor reputation. Illiac IV, when properly used, exceeded the performance of either of the others, but again was rather poor for scalars. It was a parallel processor, in that it consisted of an array of 64 processors, each capable of communicating with its nearest neighbors and operating in lock-step with each other on instructions issued by a central instruction unit.

These Class V machines are all but gone now, having been superseded by the Class VI CRAY-1, and Cyber 205. Burroughs had the BSP which it later dropped when Burroughs top management was reorganized. The BSP was organized as a parallel processor, the others as pipelined machines. With the departure of the BSP, we have no commercially available multiprocessing type of supercomputer. Denelcor is building a 4 processor system for the U.S. Army which will be finished by the end of 1982. Experiences with it will help determine the future for systems with a large number of processors operating concurrently.

The CRAY-1's performance is fairly well established now, with 39 (as of April 1982) systems in the field. As seen in Figure 11, its performance range is rather wide, from 15 to 160 MFLOPS (the former being an expected minimum, the latter the peak performance).

There have been several upgrades of the CRAY-1. First the 1K bit memory chip was replaced by a 4K chip, allowing the memory to grow to 4 Megawords. The second upgrade is the dual processor sharing a common memory. The clock was also speeded up to 8 nanoseconds (ns) from the original 12.5ns (not yet announced, the 8ns could be as much as 10ns).

A CRAY-2 is now under construction. A preliminary announcement indicated a level of performance 6X the expected minimum and 12X the peak of the CRAY-1. This is shown in Figure 11 with a 1985 introduction time. The CRAY-2 presumably will have 4 processors operating at a 4ns clock time. The entire system, with 32 Megawords and less than 4' x 4' in cross-section, will be immersed in chilled water for cooling. According to Cray, it will be available in 1984. There is no information as to when it will have software to allow for the performance promised. Cray also has plans to upgrade this machine before 1990, perhaps by going to more processors.

CDC and Burroughs competed for the opportunity of building the 1 Gigaflop machine required by NASA/Ames for its Numerical Aerodynamic Simulator facility. In previous studies Burroughs had proposed a 512 processor system and CDC an eight-pipe system along the lines of the Cyber 205.

In Figure 11, we have shown a Cyber 2XX which should fairly well represent the capabilities of the CDC proposal. It will have to have a peak rate of close to 8 Gigaflops in order to meet the required sustained rate of 1 Gigaflop. Because the advances in VLSI technology will allow a factor of approximately 2.5 improvement in the time frame for construction, the expected minimum rate is shown as 40 MFLOPS.

This system also should have 32 Megawords of high speed memory with a backing store of approximately 256 Megawords, of somewhat lower performance.

The growth of memory size over the period of time since 1965 is shown in Figure 12. None of the machines discussed will have more than 64K bits per chip before 1990. Most of the machines discussed have had memories of the size of 100,000 words per Megaflop of performance.

The Cyber 2XX, no doubt will be available before 1990, but is shown there for simplicity and because there is no specified date for first delivery as yet. Projecting into the 1995 time frame does not indicate much more than a 5 fold improvement to be expected from this technology.

Other manufacturers who may be competing with this style of architecture during the period being discussed are Fujitsu and Hitachi. Each claims to be constructing machines more powerful than the CRAY-1, to be made available within the next few years. Where they go from there would be difficult to establish at this time.

In this country IBM and Trilogy have spoken openly of having integrated array processors attached to their highest performing machines. This may bring the sequential processors to a level just below the aims of Cray Research and CDC.

The costs for very large systems as first introduced are shown in Figures 13 and 14. Although costs are creeping up, performance and amount of memory are climbing at a much faster rate. A system such as the Cyber 2XX will probably be in the \$30M range, depending on how much memory is added. Even though the costs of memory are decreasing, demands are going up rapidly. A large memory (256 Megawords) on this system could be anywhere between \$1M and \$10M depending on whether it is MOS or bipolar RAM.

The competing architecture for high performance is that of the multiprocessor. Our experience with this architecture is quite limited. Carnegie-Mellon University has assembled a number of smaller computers into a system called Cm* (its predecessor, C-mmp was not very successful). Much is being learned on this system, but of more theoretical than practical use. No large scale applications have been run on this system. Experience with Illiac IV at NASA/Ames indicated that with careful programming, high performance could be obtained on the 64 processor system.

Numerous universities are attempting to build or at least experiment with arrays of small (mostly micros) processors. The Lawrence Livermore National Laboratory (LLNL) is building a system (S-1) for the U.S. Navy, which will initially be a 4 processors-4 memories-crossbar switch system. As mentioned above, Denelcor is building a 4 processor system for the U.S. Army.

More experience with these systems is needed before we can state whether this is the direction to take into the 1990s for extremely high performance. Processors are becoming very inexpensive as compared with memory and we should be able to assemble thousands of processors in a system if we felt that there was a real payoff.

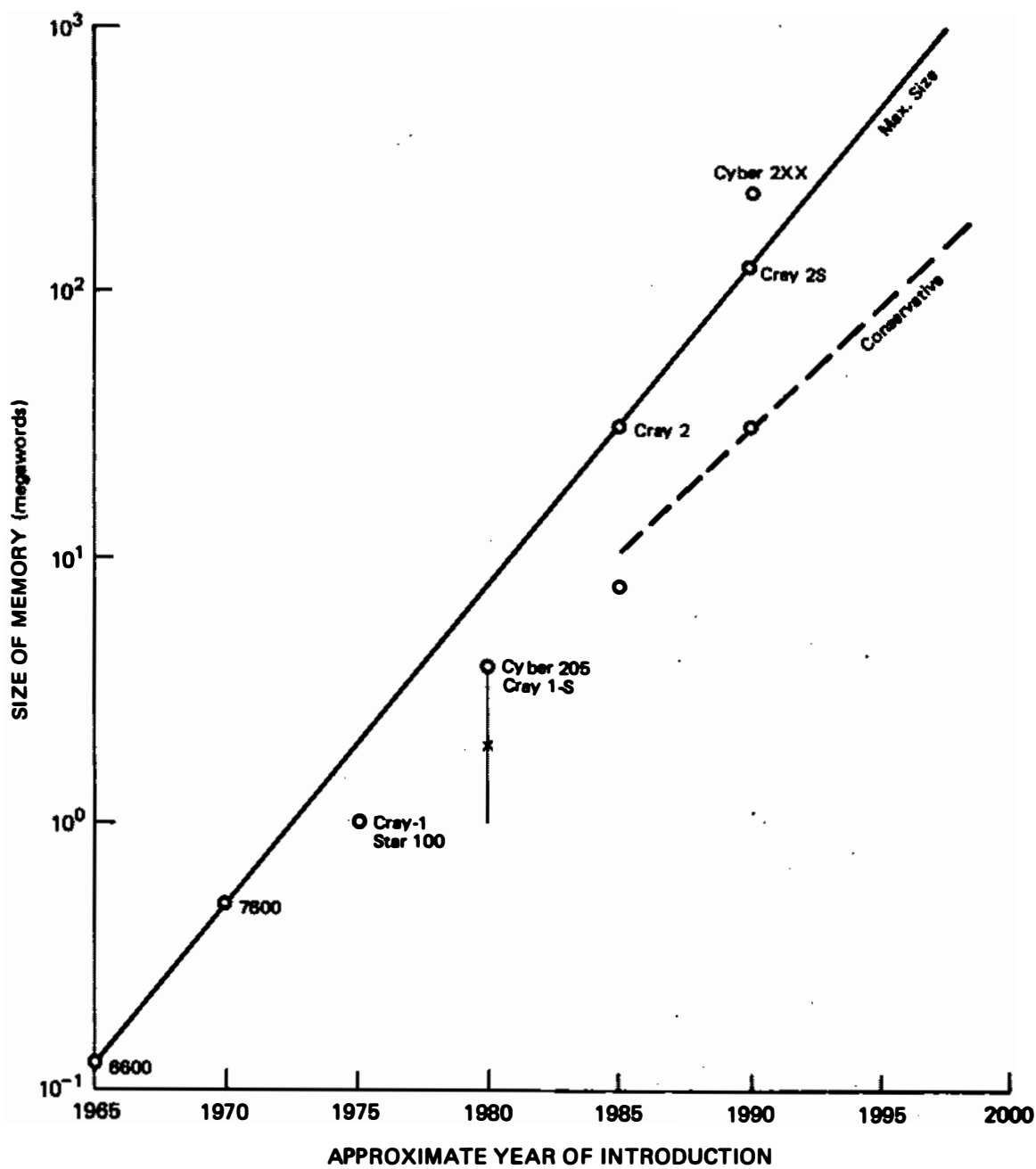


Figure 12 Growth in Memory Size for Supercomputers.

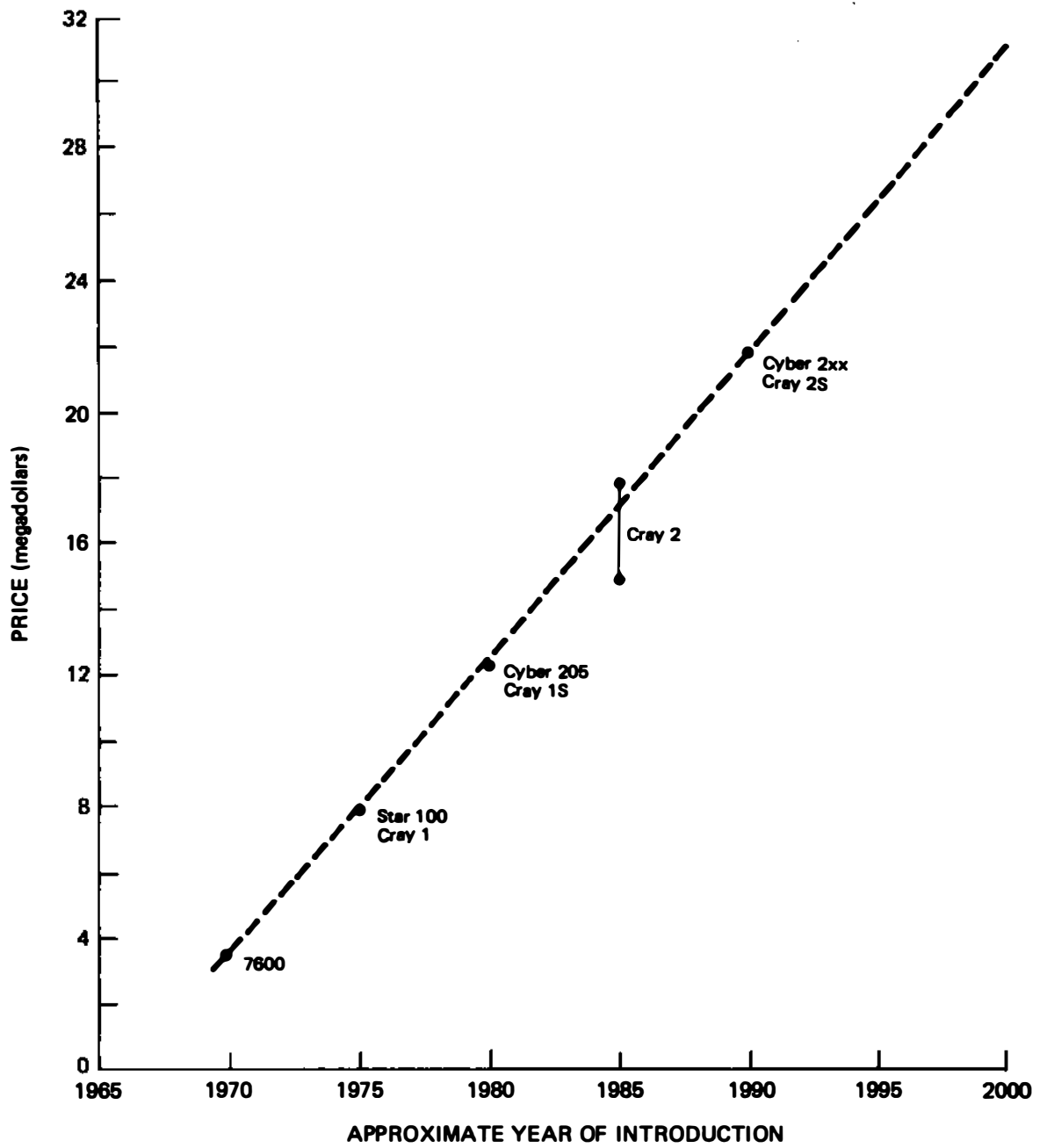


Figure 13 Cost Increase for Supercomputers.

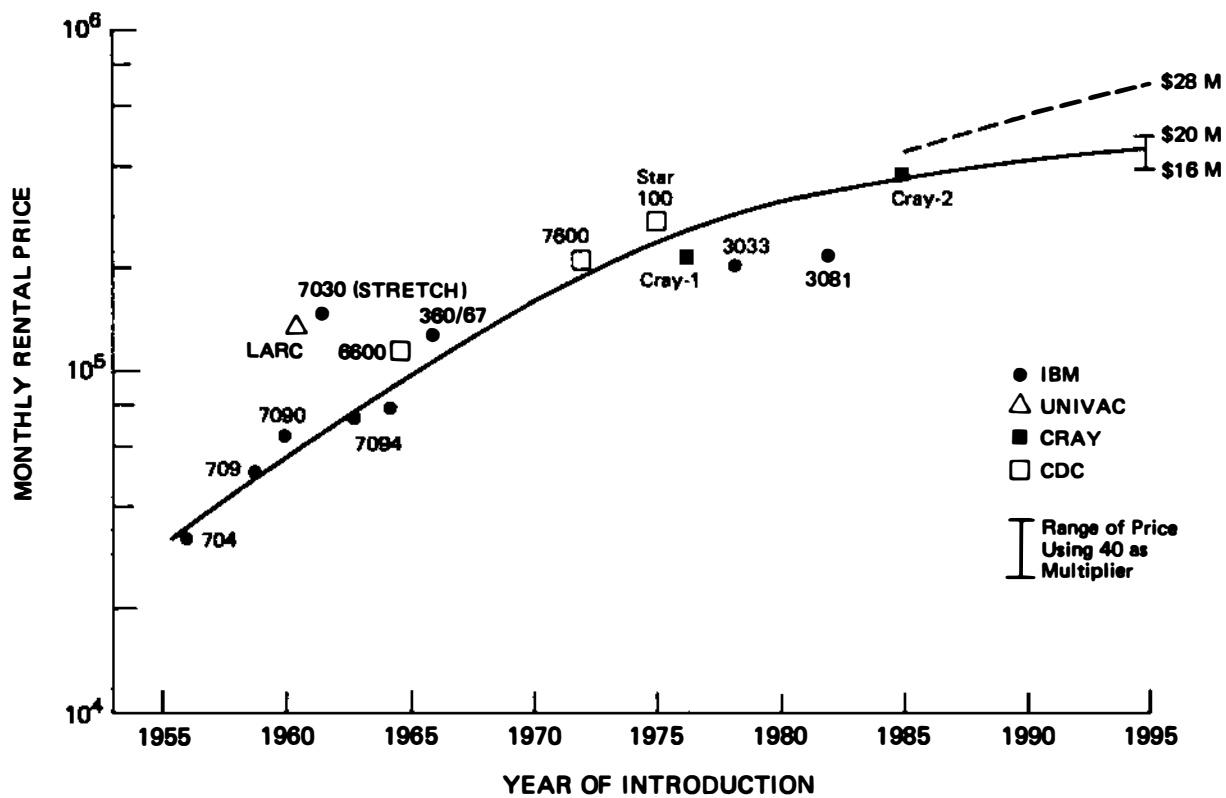


Figure 14 Monthly Rental at Time of Computer Introduction.
(Average System)

The CRAY-2 will be a multiprocessor that should help convince us of the merits of multiprocessing. Simulations in the past have indicated that 4 processors is a maximum for effective production. To test this we must build, and experiment with, a larger system, or at least simulate such a system.

PERIPHERAL EQUIPMENT

With computers of the performance class projected for 1995, it will be clearly impossible to produce printed output in the manner we have in the past. The volume would be too horrendous to contemplate! Novel ways must be found to "see" or "hear" the results of problem runs with minimal hardcopy. Recording on video magnetic or optical media digitally in real time would be the most expedient way to produce output. By that time, devices to do this will probably be available. Such devices along with softscreens for presentations will be needed in quantity. In addition, it will be desirable to provide video or graphic input.

Mass storage units with fairly high performance characteristics will also be needed. Access times should be in the microsecond range with transfer rates of billions of bits per second and storage capacities of 10^{15} bits. On-line "disk" drives may still be required for more immediate back-up storage. These could be similar or even identical to the mass-storage units. On the other hand, very large back-up memories, using low cost MOS or bubble technology might be more appropriate. It is believed that the technology to achieve results such as these now exists. Appropriate incentives have to be provided to the manufacturers in order to guarantee that these devices will actually materialize. Once feasibility is established, costs of replication should not be too high.

SYSTEM HARDWARE AND SOFTWARE COSTS PROJECTIONS

Protocols for systems communications are being established and hopefully standardized. It may take another five years before we shall be able to add component parts to networks with little additional cost or effort.

At present, the cost of setting up a network system to make a large scale computer facility readily accessible to users is high. There are a number of areas where costs are concentrated and these are mostly software related.

A good example to consider is the proposed NASA/Ames Numerical Aerodynamics Simulator (NAS) facility. From there we can project into the future to determine costs for replacements and additional software.

NAS is estimated to cost in the neighborhood of \$100M. Actually, if one included the development costs for the NAS engine this number would have to be doubled. In the time scale for completion of the engine, its cost alone could be \$30M, where one-third of this would go

for the memory. The software for the machine, if it had to be done from scratch (assuming we know how to write the specialized software for the machine), would cost at least 200 man years, of the order of \$20M. When one adds to it the network with its graphic systems, terminals, and communications, there could be an equivalent amount spent on the software. The additional hardware might be somewhat less, depending on the number of nodes and terminals.

The unfortunate situation is that the network is not well described and has had little systems expertise to define it in such a way as to satisfy a multitude of concurrent users.

The future as we see it revolves around the use of general purpose intelligent terminals for most users, tied into a network with one or more NAS's. Graphics and small data base handling can be at the local site. A front-end on the NAS can handle the large data base. If indeed it is believed that the world will move in this direction, one could implement the system hardware and software alike in a fashion permitting trivial replacements to enhance performance as new components are developed; e.g., replacing a 68,000 by a 680,000 and adding another 100M Bytes of memory at each station. Some additions could not be predicted and so would have to be made on the bus directly; e.g., an on-line movie-making machine using a video disk recorder.

If one can anticipate living within a given software environment for 10 years, the overall cost for growing would involve the cost of hardware alone.

Seymour Cray believes he can improve the large system performance by a factor of 4 or 5 every 4 years or so. Assuming the CRAY-1 capability to be between 15 and 160 MFLOPS (average scalar and peak vector performance) and the CRAY-2 90 to 2000 (CRAY-1 Serial 1 was delivered in 1976, CRAY-2 Serial 1 probably will be delivered in 1985), by 1990 we should be at 400 to 8000 MFLOPS and by 1995, 1600 to 30,000. He never defined how these improvements would be achieved.* Over this time span a factor of 10 might be achieved in component performance, especially if one were to go to Josephson Junction technology. The remaining factor of 10, if we are to achieve it, must come from architectural improvements. Perhaps we will learn to use multiprocessors by then. This implies a huge investment in reprogramming, because of incompatibilities with the present world.

However, by proper preparation of the remainder of the network, the overall job can be reduced by at least a factor of two.

If we extrapolate our curves, on the average we should expect a performance capability of 5000 MFLOPS by 1995 with a memory capacity of 500 Megawords. We should be within a few years (~year 2000) of a 4

*An upgrade of the CRAY-2 would involve, among other changes, an increase to 8 processers.

Megabit chip which would allow for a 2000 Megaword memory on that same system. The 500 Mw memory system should cost under \$10M; the CPU will cost approximately the same amount.

Since the figure is an average, depending on vector/scalar ratio, we should also mention that the vector performance could be as high as 30000 MFLOPS and scalar performance as low as 100 MFLOPS.

These figures are possible, at reasonable costs, but assume that either competition or recognition of the national need will help provide funding to construct the machines. The software costs could be \$20,000,000 or more if we continue an unstructured course. With standardization, growth in place and adequate research funds to help develop better software engineering techniques, this figure could be reduced substantially.

REFERENCE

1. Chapman, Dean R., "Trends and Pacing Items in Computational Aerodynamics," 7th International Conference on Numerical Methods in Fluid Dynamics, Proceedings Stanford 1980, Springer-Verlag, 1981, pp 1 - 11.

APPENDIX C

STATUS OF COMPUTATIONAL FLUID DYNAMICS AND
PROSPECTS FOR IMPROVED NUMERICAL METHODS

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ABSTRACT

The status of computational fluid dynamics is assessed. Projections are then made based upon this assessment for the computer requirements to numerically simulate flows past complete aircraft configurations at flight Reynolds' numbers. Prospects for improved numerical method efficiency are considered and estimates of computational fluid dynamics capability during the next five years are made.

INTRODUCTION

To explain the formation of the Grand Canyon in the past, one should look at the muddy Colorado River today carrying away part of the canyon floor. Similarly to predict the future, at least the near future, one should look at what is going on today. More than fifty computational fluid dynamicists throughout the United States and some from Europe were asked to describe the problems they have solved in recent years and those they are now working on, the equations solved, the numerical methods used, the number of mesh points and computer time required for solution, and the computer used. In addition the views of several leading scientists on the prospects of computational fluid dynamics were obtained. Although there is no unanimity of thought many of their ideas are presented herein.

The assessments, projections, and analysis contained in this report are concerned primarily with finite difference calculations using grids of mesh points to discretize the volume of moving fluids. The report does not concern itself with panel, finite element, or vortex tracking calculations. Panel methods today represent a mature technology. Such calculations using as many as 3×10^3 panels can fairly routinely represent a linear inviscid flow about complete aircraft configurations, including nacelles, tails, etc. Too little information was received on finite element calculations to be discussed herein. The finite element approach to a large extent parallels and in some cases leads the development of the finite difference approach. Noteworthy calculations, particularly in France, about complete aircraft are being attempted today. It is believed that the status and future development prospects of the finite element approach are not too unlike that of the finite difference approach to be discussed. The vortex tracking approach still appears to be a very young discipline undergoing rapid development. How quickly it will mature is an open question today.

The development of computer hardware and architectures, expected to have perhaps a much larger effect on computational fluid dynamics than numerical method development, is also not addressed by this report. Similarly, the prospects of turbulence modeling, a key element in the simulation of high Reynolds' number flow by solving the Reynolds averaged Navier-Stokes equations, is not addressed.

Much of the information and analysis presented within was generously provided by V. Peterson, NASA/Ames Research Center, E. Murman, Massachusetts Institute of Technology, J. South, NASA/Langley Research Center, and T. Holst, NASA/Ames Research Center.

STATUS

More than ninety data points, each representing a calculation of a fluid flow problem, were used to obtain the results shown in Figure 1. Each shaded region of the figure represents the range in number of grid points and computer time required to solve a given class of problems. Although the computational problems were solved on several different computers, each computational time was converted to the equivalent time required if the problems were solved on a CDC 7600 computer. The spread in computer time required for a fixed number of grid points for a given class of problems is caused by differences in the types of problems solved, the numerical methods used, the number of iterations or time steps required, and to some degree on the uncertainties in the conversion factors used to relate the computer timings on the machines actually used to that of a CDC 7600. Nevertheless, the fact that the problem classes seem to form coherent structures is remarkable and can be used to assess the present state of computational fluid dynamics and also to project trends in the near future.

Transonic Flow

Probably the greatest success story of the last decade in computational fluid dynamics is that of transonic flow. Two dimensional transonic flow calculations, solving either the small disturbance or full potential flow equations, can predict the flow about airfoils in less than half a minute on computers readily available in the United States today (airfoil, steady full potential equations, 4.5×10^3 grid points, 5-10 seconds on a CDC 7600, Holst, 1978). This class of problems lies nearly off the graph of Figure 1 and explains why computations have virtually eliminated experiment in airfoil design.

In three dimensions these same equations can be numerically solved to predict steady transonic flows about realistic aircraft shapes in computer times short enough for many routine engineering applications (wing-fuselage, small disturbance equations, 10^5 grid points, 20 minutes on an IBM 3033--approximately half as fast as a CDC 7600) (Ref. 1). In general, the small disturbance calculations, which apply boundary conditions on mean boundary surfaces, are faster and can handle more complex geometries (nacelles, pylons, canards, winglets, and tails) than the full potential calculations, which apply boundary conditions on the actual boundary surfaces. Considerable effort is under way to generate mesh systems about complex geometrical bodies for full potential calculations (wing-body-nacelle-pylon with

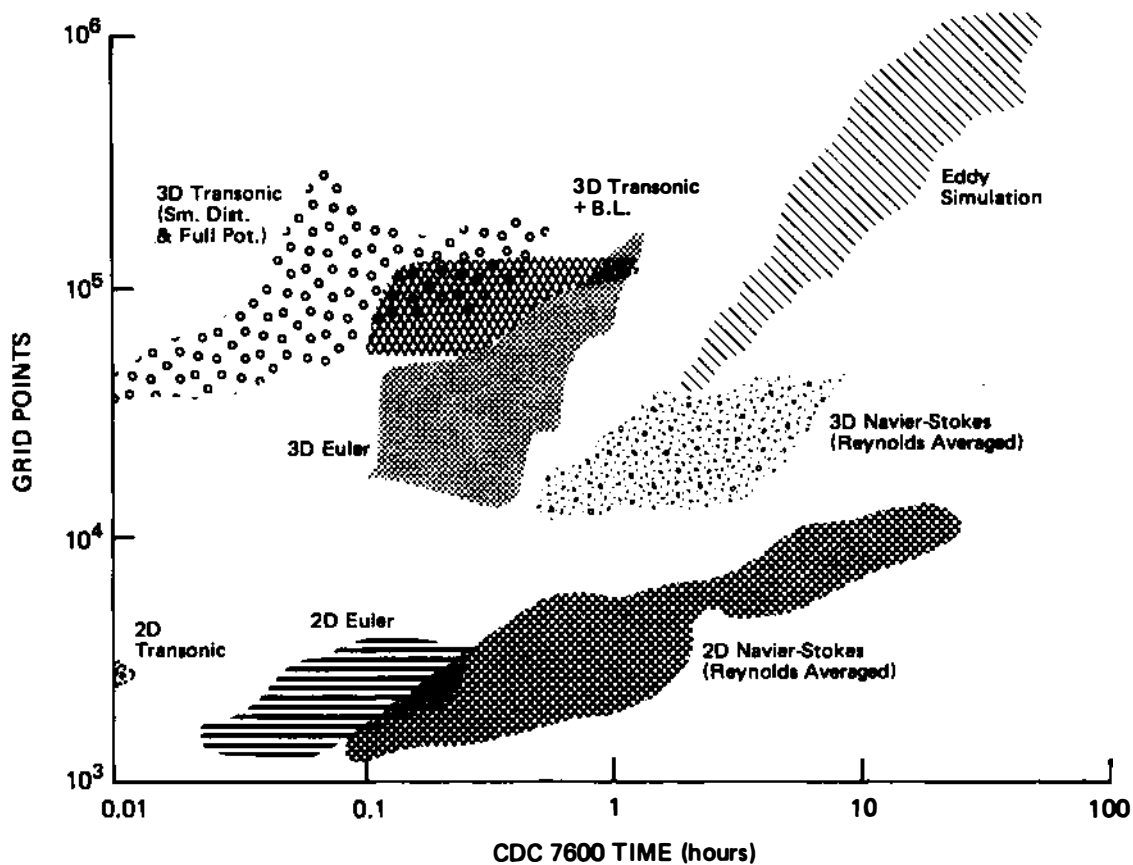


Figure 1 Present Usage of Computer Memory and Time for Various Computational Fluid Dynamics Problem Classes.

body fitted coordinates, full potential equations, 8.4×10^4 grid points, 38 seconds for grid generation plus 285 seconds for solution on a Cray 1 computer--approximately two to four times the speed of a CDC 7600 (Ref. 2). Viscous effects can also be included by solving in addition boundary layer equations.

The Euler Equations

The Euler equations are now receiving considerable renewed interest because of recent advances in numerical method development and the availability of powerful computers. We can see from Figure 1 that these equations require roughly an order of magnitude more computer time for solution than the transonic flow equations for similar flow problems with an equivalent number of grid points. These equations are, however, far more general and can describe inviscid flows that are subsonic, transonic, or supersonic. Two dimensional flow solutions can be obtained in computer times small enough for some routine engineering applications. Some recent three dimensional Euler calculations for flows past wing-bodies have been made in computer times fairly competitive with those using the transonic small disturbance for full potential equations (wing-body, Euler equations, 2.5×10^4 grid points, 4 minutes on a CDC Cyber 203--approximately the speed of a Cray 1; wing-body, Euler equations, 5×10^4 grid points, 4 to 10 minutes on a Cray 1) (Refs. 3 and 4).

Navier-Stokes

The shaded region of Figure 1 representing the range of two dimensional Reynolds averaged Navier-Stokes calculations is fairly extensive. The large spread in computer time required for a fixed number of grid points is caused primarily by two reasons. First, some problems had unsteady solutions (buffet, aileron buzz, and oscillating airfoils) and were run for long times compared to flow problems that converged to steady state solutions. And second, many of the data points composing this region represent tests on proposed turbulence models. The models ranged from simple algebraic eddy viscosity models to complex multi-differential-equation models. For some models the computer time required to numerically integrate the model equations was larger than that for the Reynolds averaged Navier-Stokes equations themselves and this caused the overall computing times to be long.

The shaded region representing three dimensional Reynolds averaged Navier-Stokes calculations is more compact although it does contain results from several different problems at high Reynolds' numbers using different numerical methods (body of revolution at angle of attack, Reynolds averaged Navier-Stokes equations, 3.2×10^4 grid points, 1.5 hours on a CDC 7600 [Ref. 5]; Hemisphere-cylinder at angle of attack, Reynolds averaged Navier-Stokes equations, 1.9×10^4

grid points, 3.5 hours on a CDC 7600 [Ref. 6]; swept wing in a channel, Reynolds averaged Navier-Stokes equations, 3.6×10^4 grid points, 7 hours on a CDC 7600 [Ref. 7]).

Eddy Simulations

The most demanding class of problems of computer resources is eddy simulation. The elongated shaded region representing this class covers almost two orders of magnitude in computer memory and time required for solution. Computation time varies approximately linearly with the number of grid points used, indicating that differences in numerical method and problems solved are minor causes affecting overall computing times. The problems solved include large eddy simulation of turbulent shear flows (3-D incompressible Navier-Stokes equations, 3.3×10^4 grid points, 2 hours on a CDC 7600 [Ref. 7]), homogeneous turbulence (3-D incompressible Navier-Stokes equations, 2.3×10^6 grid points, 20 hours on the Illiac 4--approximately 4 to 5 times faster than a CDC 7600, [Ref. 9]), and boundary layer transition (3-D incompressible Navier-Stokes equations, 5.6×10^5 grid points, 12 hours on the Illiac 4, [Ref. 10]).

PROJECTIONS

Using the data of Figure 1 representing the present status of computational fluid dynamics, it is possible to estimate the computer time required for the solution of the Reynolds averaged Navier-Stokes equations and the Navier-Stokes equations (eddy simulation) for flows about complete aircraft. Figures 2(a) and (b) show these two projections.

The broken line passing through the center of the shaded region for the three dimensional Reynolds averaged Navier-Stokes equations assumes that the computer time required to solve these equations will vary linearly with the number of grid points used. This behavior was observed for the eddy simulation calculations of Figure 1. The equation for this line is

$$T = 10^{-4} N$$

where N is the number of grid points and T is the required computation time in hours on a computer with the speed of a CDC 7600. The equation also assumes that the computer's central memory is always sufficiently large that the data transfer times into and out of it do not add significantly to the overall computing time. The coefficient 10^{-4} appearing in the equation could be changed by a factor of two larger or smaller with the line still passing through the shaded region representing the 3-D Reynolds averaged Navier-Stokes solutions of Figure 1.

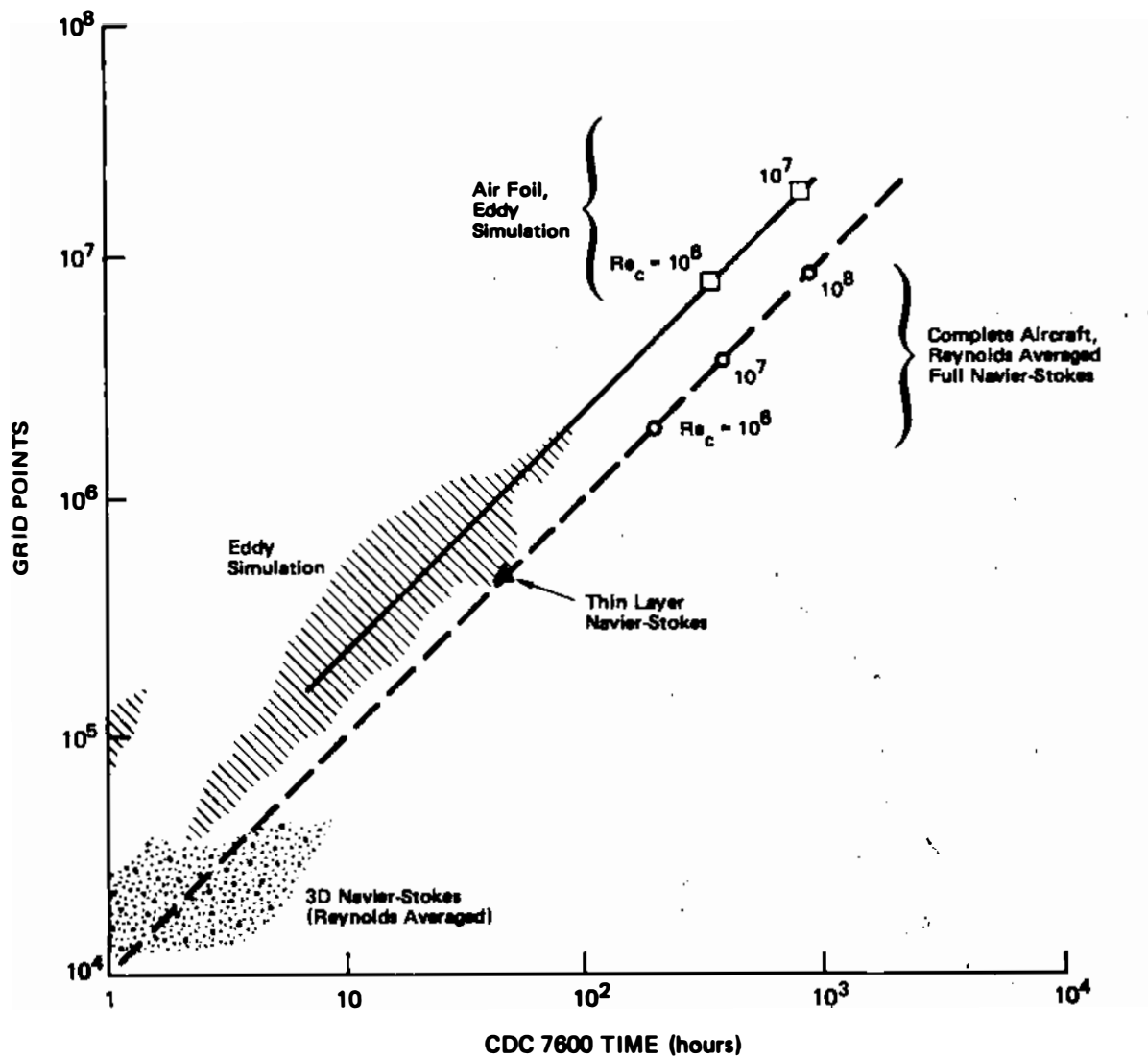


Figure 2 Projected Computer Requirements.
(a) Computer Time 1 to 10^4 Hours

-----Equation appears on page 84.

————Equation appears on page 89.

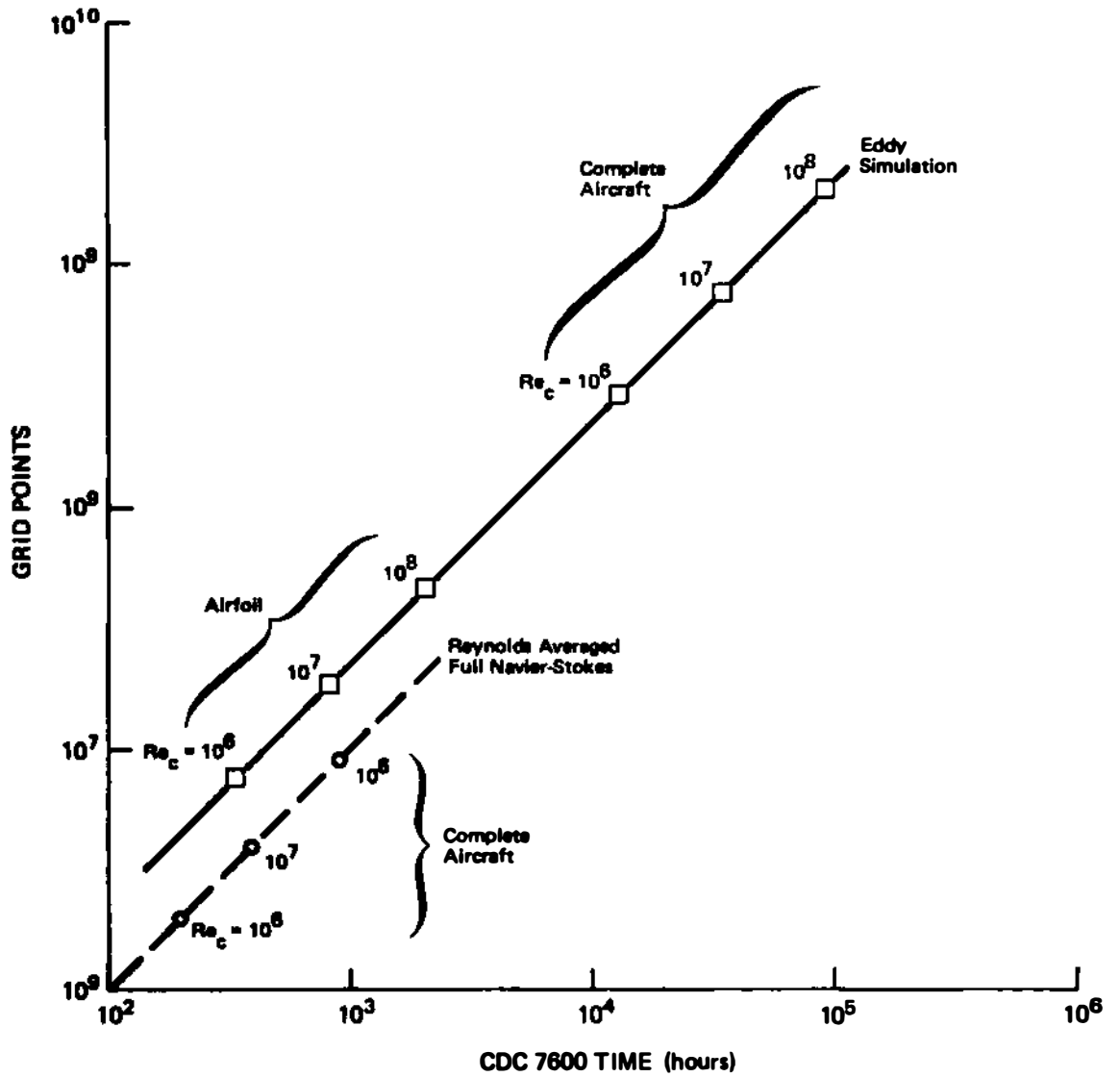


Figure 2 Projected Computer Requirements.
(b) Computer Time 10^2 to 10^6 Hours

Three points are plotted on the broken line of Figures 2(a) and (b) corresponding to D. R. Chapman's 1979 estimates for the number of grid points required to calculate the flow about a complete aircraft (wing-body-tail and nacelles) in cruise at Reynolds' numbers 10^6 , 10^7 and 10^8 using the Reynolds averaged equations (Ref. 11). The number of grid points corresponding to these three calculations are 2×10^6 , 4×10^6 , and 9×10^6 respectively. The total number of grid points in just the upper or lower surface boundary layer of the wing of chord C and aspect ratio AR is given by $N_x \times N_y \times N_z$ where N_x , N_y and N_z are the number of points along the chord, across the boundary layer, and along the span, respectively, and are given by

$$N_x = 4.5 \frac{1}{Re_C}^{0.2}$$

$$N_y = 20$$

and

$$N_z = 2.25 AR \frac{1}{Re_C}^{0.2}$$

These estimates for N_x and N_z correspond to grid points spaced approximately one and two boundary layer thicknesses apart along the chord and span directions respectively. This spacing should be sufficient to resolve the Reynolds averaged Navier-Stokes equations with the effects of subgrid scale motions accounted for by turbulence modeling. Similar estimates were made for the fuselage, tail, nacelle and pylon surfaces. The total number of grid points for a complete aircraft was estimated by adding the totals for each component element boundary layer and wake grid plus an overall grid with spacings chosen to resolve only the inviscid flow about the aircraft.

The three dimensional high Reynolds' number solutions in the shaded region at the lower corner of Figure 2(a) are actually thin layer approximations because either the viscous terms in the stream and spanwise directions were deleted from the governing Reynolds averaged equations or the grid point spacing was so coarse in those directions that these viscous terms were not adequately resolved. In either case the grid points spacings were much larger than the estimates of D. Chapman, although all of the terms normally appearing in the Euler and boundary layer equations were resolved. For many viscous flows these are the only terms requiring resolution. For a wing at $1/Re_C = 10^6$ with $AR = 4$, Chapman's estimates correspond to an upper surface boundary layer grid of 71 points along the chord, 20 across the boundary layer, and 141 along the span, or 2×10^5 total grid points. For thin layer theory, using estimates by South and Thames, with 60 points along the chord, 20 across the boundary layer, and 40 across the span, a total of only 5×10^4 are required, or one fourth as many as are needed to solve the Reynolds averaged full Navier-Stokes equations at $1/Re_C = 10^6$. The thin layer estimates do not depend on Reynolds number and assuming that estimates similar

to that for the wing can be made for the fuselage, tail nacelle, and pylon surfaces, the total number of grid points to solve the Reynolds averaged thin layer Navier-Stokes equations is $N_{T.L.N.S} = 5 \times 10^5$ grid points, or approximately one fourth the number required to solve the Reynolds averaged full Navier-Stokes equations at $1/Re_c = 10^6$. This data point is also plotted on the broken line of Figure 2(a). In theory a solution for the flow about a complete aircraft configuration could be obtained in 50 hours (two days of computing) on a machine with the speed of a CDC 7600 assuming that

- (a) the thin layer Navier-Stokes sufficiently describe the flow,
- (b) a suitable turbulence model can be devised to account for all significant subgrid scale motion effects,
- (c) the topological problems associated with nesting grids about aircraft component elements and interfacing each with an exterior inviscid grid can be solved,
- (d) the computer's central memory is sufficiently large so that data transfer time into and out of it does not add significantly to the computing time, and
- (e) the computing time required for solution of the three dimensional equations scales linearly with the number of grid points used.

Assumptions (b) and (c) are major hurdles that must be leaped before realistic solutions will be obtained. For assumption (d) Chapman estimated the number of words of storage for solving the Reynolds averaged equations to be approximately 30 times the number of grid points. This factor includes the metric coefficients, dependent flow variables, and turbulence quantities associated with each grid point. At the expense of additional computing, this factor could be reduced. The last assumption (e) is probably not too far off the mark. Although the time step size that a solution can be advanced during each step is still limited, even with today's implicit numerical methods, and the number of steps required for a solution is often large, the computing time depends primarily on the number of grid points used and not, as was formerly true with explicit methods, on such factors as the finest grid point spacing and the largest speeds and kinematic viscosities in the flow field. Also, the treatment of boundary conditions at grid interfaces, though a significant program logic problem, should not increase the computing times significantly over that required for a single grid calculation with an equal number of total grid points. The number of boundary points is always expected to be small compared to the total number of grid points.

The projected computer times required for the solution of the Reynolds averaged full Navier-Stokes equations for flow past a complete aircraft at Reynolds' numbers $1/Re_c = 10^6$, 10^7 , and 10^8 are from Figure 2(a) 2×10^2 , 4×10^2 , and 9×10^2 hours respectively on a computer with the speed of a CDC 7600. These projected times depend on assumptions (b), (c), (d), and (e) of the last paragraph.

The solid line of Figures 2(a) and (b) represents the projection of the computing time required for the solution of the complete Navier-Stokes equations on a scale small enough to correctly simulate all significant turbulent eddies. This projection depends only on assumptions (c), (d), and (e) above. The data points plotted along the line are taken from Chapman's 1979 estimates of the number of grid points required for the correct large eddy simulation of the flow past an airfoil and a complete aircraft at various Reynolds' numbers. The equation of the solid line is

$$T = 4.5 \times 10^{-3} N$$

where again N is the number of grid points used and T is the required computation time in hours on a computer with the speed of a CDC 7600. The coefficient 4.5×10^{-3} is approximately half that for the Reynolds averaged equations. This is caused primarily by the fewer number of equations solved in the eddy simulation problems. Most of the problems required the solution of only the incompressible Navier-Stokes equations and of course there were no turbulence model equations to be solved.

PROSPECTS

In general terms, a numerical solution for a fluid flow problem is obtained as follows:

- (1) The flow field is discretized into small volumes by a grid chosen fine enough to resolve all characteristic lengths of the flow.
- (2) The governing differential equations and boundary conditions are approximated at grid points by algebraic finite difference equations of suitable accuracy.
- (3) An initial value for the solution is assumed.
- (4) A strategy or procedure is devised to advance the solution in time by discrete time steps until the solution depends only on the approximating difference equations and imposed boundary conditions and no longer on the guessed initial solution. At this time the solution can be either stationary or time dependent.

During the last decade we have witnessed remarkable progress in devising efficient numerical methods, strategies, and procedures. Three of these are the development of

- (i) fully implicit methods,
- (ii) multi-grid procedures, and
- (iii) psuedo-time stepping strategies.

Before the above developments, existing explicit numerical methods could only allow information to travel slowly from one grid point to its nearest neighboring grid point. The pace that information could travel during a time step was determined from stability conditions to

be the shortest distance between any two points of the grid. Because many calculations of engineering interest contain highly nonuniform grids, many time steps were needed before information could travel completely to even nearest neighbors in stretched regions of the grid. Until information can travel throughout the flow field from boundary to boundary and back again, for some problems many times, the solution cannot in general arrive at a state independent of the initial guess; hence long computation times were often required.

The development of fully implicit methods in the mid 1970s improved numerical efficiency by orders of magnitude. Time step sizes were no longer limited to the transit time between nearest neighbors by stability conditions. They could be chosen more freely, in some cases several orders of magnitude larger, and the time required to solve a given problem was reduced to a small fraction of that previously required. The time step size is, however, still limited. Too large a size will result in inaccuracy. This can be illustrated fairly simply by considering a difference approximation to a first derivative of a smooth function.

$$\frac{\partial f}{\partial x} \approx \frac{f(x+h) - f(x)}{h}$$

As the grid point spacing h is reduced, the approximation, according to the usual rules of calculus should improve. On a computer with finite precision, the approximation will at first improve then will grow worse. A 32 bit computer word has six or seven significant figures, the last one or two of which are highly subject to roundoff error after a few arithmetic operations. As h is reduced the difference approximation eventually is determined by error alone. For explicit calculations such error considerations are not as important because the difference terms appearing in the approximation equations are multiplied by a time step size Δt of the order of h . For implicit calculations of high Reynolds' number flows, where h can be as small as the order of l/Re_c and Δt an order or two larger than h , accuracy can be a problem (particularly if half word calculations are used in order to double the available memory of the computer).

Multi-grid procedures can be used to alleviate this problem. To gain some understanding of this type of procedure, consider a three dimensional uniform or nonuniform grid of $128 \times 128 \times 128 = 2 \times 10^6$ points. The total grid will be called the fine grid. A second grid can be formed by deleting every other grid point. This second grid contains $64 \times 64 \times 64$ points, one eighth as many as the fine grid. We can continue in this manner forming grids each with one eighth as many points as the previous one. This can, but need not, be done seven times with our original 128^3 grid. If we then advance the solution on the fine grid, using even perhaps an explicit method, with a small time step, then advance the solution on the next finest grid using the same method with a time step twice as large, and so on, we have a means of transmitting information across the entire flow field in a few steps. Information calculated locally on the fine grid can catch an express that skips every other stop, transfer to another express

that skips still more stops, etc., and travel very efficiently about the flow field. Information can travel in the opposite direction, coarse to fine, as well because every point of a given grid is a member of each finer grid and interpolation procedures can be used to determine the values at skipped points from coarser grid calculations. To estimate the amount of work in the calculation we need only count the number of times the fine grid solution was advanced. Because each grid contains only one eighth the number of points of the previous finer grid, the calculation time spent on all grids except the fine grid is a small percentage of that spent on the fine grid, unless one of the coarse grids was advanced many times more often. Finally, the error problem discussed earlier can be alleviated because the time step size used in each grid can be scaled to the grid point spacing so that $\Delta t/h$ is always of the order of unity.

For flows with steady solutions psuedo-time stepping strategies can be used to advantage. To gain some insight of this type of strategy we can consider a three dimensional nonuniform grid. The solution is advanced on this grid at each point using a time step scaled to the local grid point spacing. The solution is then obtained on a warped time surface, which is unimportant if the solution converges to a steady state. The time steps can be chosen so that the local CFL (Courant-Fredrichs-Lewy) number is everywhere near unity, a choice usually associated with small numerical dispersion and dissipation errors. The local time stepping strategy is easier to implement than multi-grid procedures but information transit distances are much more limited, approximately from neighbor to neighbor everywhere throughout the flow field, though not nearly as limited as conventional explicit methods on highly stretched grids.

At present, to solve the transonic flow equations (small disturbance or full potential), the Euler equations, and the Reynolds averaged Navier-Stokes equations requires roughly 2×10^2 , 5×10^2 and 2×10^3 iterations respectively. For some transonic flow calculations, fully implicit methods and multi-grid procedures have already reduced the required number of iterations to approximately 50 and 20, respectively, with the multi-grid procedures using somewhat more than twice the computer time per iteration. Also, recent Euler calculations using both multi-grid and psuedo-time stepping procedures have significantly reduced the number of iterations required for solution. Research is currently going on to apply multi-grid procedures to the compressible Navier-Stokes equations. In the next few years using fully implicit, multi-grid and other procedures to be devised, it appears possible to reduce the number of iterations required to advance the solution of the Navier-Stokes equations to a state independent of the initial condition to approximately 20 iterations, each requiring only about twice the computer time now used per iteration. To continue to advance an unsteady solution would require of course more time step iterations. Such a reduction would represent a nearly two orders of magnitude decrease in the computer time required to solve a given viscous compressible flow problem, a shift in the ordinate of Figure 2(a) and (b) by nearly 10^2 .

A possible scenario for the next five years is as follows. Nested grid systems about complete aircraft are developed and perfected for use in solving the transonic full potential equation. Boundary condition procedures are devised and perfected to couple the solutions calculated on separate grids at common interfaces. The Euler equations are then solved using the same nested grid procedures developed for the full potential equations. Meanwhile, numerical procedures, perhaps multi-grid procedures, are developed that can accurately and rapidly propagate information throughout a single grid for solving the compressible Navier-Stokes equations. These numerical procedures are then applied to a nested grid system about a complete aircraft configuration, using the previously devised inter-grid boundary techniques for the Euler equations, to solve the Reynolds averaged thin layer Navier-Stokes equations with hopefully improved turbulence models. If the assumed possible improvement in numerical efficiency is achieved, nearly a two orders of magnitude increase, the above viscous flow calculation for a complete aircraft using 5×10^5 grid points would require approximately the same computer time that three dimensional Reynolds averaged thin layer Navier-Stokes calculations past simple body geometries are using today. Complete aircraft calculations solving the Reynolds averaged full Navier-Stokes equations, at Reynolds' numbers $1/Re_c = 10^6, 10^7, \text{ and } 10^8$ (see Figure 2(a)), however, would require the development of advanced fast computers.

CONCLUDING REMARKS

The numerical techniques being worked on today offer the promise of a significant increase in computational fluid dynamics capability. These techniques include the development of nested grid systems about complex shaped bodies, boundary condition procedures at grid interfaces, fully implicit methods for integrating the equations of motion, and multi-grid procedures to speed convergence by rapidly communicating information throughout the flow field. These techniques should adapt well to present and foreseeable computer architectures for solving large three dimensional problems because large data base problems should offer more opportunities to form long vectors, etc. It is possible in the next five years to calculate the compressible viscous flow about complete aircraft configurations to the same resolution and with the same computational effort being used today for simple geometrical shapes. Improvements in computer hardware and turbulence modeling can further extend this capability.

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APPENDIX D

TYPICAL COSTS OF AERODYNAMIC DESIGN VERIFICATION IN TEST FACILITIES OR BY CFD

In the course of development of a new aerospace vehicle, the project teams in industry utilize a variety of test facilities differing widely in size, capability, and cost. The choice is dictated by convenience and economy; as much as possible will be done in in-house or at neighboring facilities at low speed and cost, depending upon a final check in a national facility at higher Mach number or Reynolds' number. Table 1, showing the wind tunnels used by the Boeing Company on their last three transport aircraft projects, is typical of industry practice.

The wide variety of possible problems requiring test (see Table 1 of Chapter IV), the diversity of test facility capabilities and costs, and the differences in accounting practices at different laboratories, all combine to complicate the cost picture. Existing facilities vary greatly in the convenience of setting up or changing the model, and in the rapidity of data collection. Nevertheless, it is common practice to quote costs in dollars per hour of occupancy. This reflects the fact that a large block of costs is incurred whether the air is blowing or not; labor, maintenance, overhead, depreciation are in this category. Since the ratio of "air-on" to "occupancy" time can vary between 25 percent and 80 percent, costs which are only incurred when running are separately billed; power costs are usually the major component here. Finally, since the degree of automation in the data collecting and reduction changes considerably the number of data points per "air-on" period, some facilities make a separate charge for data handling, usually around \$1 to \$3 per data point. The above comments apply broadly to the wind tunnel or the engine test facility.

TABLE 1. Typical Transport Aircraft Testing Costs (1981 Base)

These costs are estimated from past Boeing experience and actual billings.

TUNNEL	TYPE	SIZE	BASIC COST* Per Occupancy Hour	POWER Per Occupancy Hour	TOTAL COST Dollars Per Occupancy Hour
Ames	Transonic Atmospheric	14'	1450	400	1850
Ames Unitary	Transonic Pressure	11' X 11'	1750	850	2600
Boeing	Transonic Atmospheric	8' X 12'	2355	160	2515
Calspan	Transonic Pressure	8' X 8'	2260	340	2600
Ames	Low Speed Pressure	12'	1000	400	1400
Boeing	Low Speed Atmospheric	5' X 8'	475	10	485
Convair	Low Speed Atmospheric	8' X 12'	550	80	630
Rockwell	Low Speed Atmospheric	7-3/4' X 11'	550	80	630
University of Washington	Low Speed Atmospheric	8' X 12'	235	20	255
Vertol	Low Speed Atmospheric	20' X 20'	1600	200	1800

*Includes labor, maintenance, depreciation, computing, etc.

The industrial corporation testing new designs at NASA facilities is charged a base cost derived as follows (cost figures are for the NASA Ames Unitary Plan Wind Tunnel Facility, in FY 1981 dollars):

$$\begin{aligned}
 \text{Cost} = & \left[\begin{array}{l} \text{Civil Service Labor + Travel} \\ (\$1,259,346) + (\$5,185) \end{array} \right] \times \begin{array}{l} \text{Center Overhead} \\ (1.87) \end{array} \left. \vphantom{\begin{array}{l} \text{Civil Service Labor + Travel} \\ (\$1,259,346) + (\$5,185) \end{array}} \right] \times \begin{array}{l} \text{Hqs. Overhead} \\ 1.1 \end{array} \\
 + & \left[\begin{array}{l} \text{Contract Support} \\ (\$1,048,320) \end{array} \right] \times \begin{array}{l} \text{Contract Administration} \\ (1.87) \end{array} \left. \vphantom{\begin{array}{l} \text{Contract Support} \\ (\$1,048,320) \end{array}} \right] + \left[\begin{array}{l} \text{Facility Maintenance} \\ (\$1,106,900) \end{array} \right] \\
 + & \left[\begin{array}{l} \text{Personal Property} \\ \text{Depreciation} \\ (\$329,789) \end{array} \right] + \left[\begin{array}{l} \text{Real Property Depreciation} \\ (\$207,008) \end{array} \right] = \$5,301,543/\text{year}
 \end{aligned}$$

Initial Capital Investment is excluded from real property depreciation. Total chargeable occupancy is estimated on the basis of (shifts per day) X chargeable occupancy X (hours per shift week) X (operational weeks/year) = total occupancy. Thus,

$$(2.75) \times (.81) \times (40) \times (44) = 3920.4 \text{ hours/year}$$

Cost per occupancy hour =

$$\frac{\text{Real Property Depreciation}}{8760} + \frac{\text{COST-Real Property Depreciation}}{\text{Est. Chargeable Occupancy hrs.}}$$

$$\frac{\$207,008}{8760 \text{ hrs.}} + \frac{\$5,301,543 - \$207,008}{3920.4 \text{ hrs.}} = \$1,323/\text{hour}$$

Additional costs are due to energy consumed (\approx \$17 per megawatt hour) and data reduction computer usage (\$1 to \$3 per data point).

This implies an average total cost billed to the corporation of about \$2,000 per occupancy hour, somewhat less than the figures in Table 1--the differences are within the uncertainty band. Both base cost and power cost are increasing with time as a result of inflation and electric power rates; the total cost increase lies between 5 percent and 10 percent per year.

To these figures the company must add its own costs for models and for the salaries and travel expenses of its engineers arranging or attending the tests. Table 2, again from Boeing, shows the range typical of a number of transport aircraft models required. For the entire series of wind tunnel tests on a new design, roughly \$10 M is expended on models. Adding this to the wind tunnel occupancy and power costs, the present cost of aerodynamic design verification in wind tunnels (Table 3) is about \$30 to \$40 M for a major civil transport program. Grumman independently cites comparable expenditures for military fighter programs, with model costs around

TABLE 2 Wind Tunnel Model Planning Costs--Transport Aircraft (1982 Dollars)

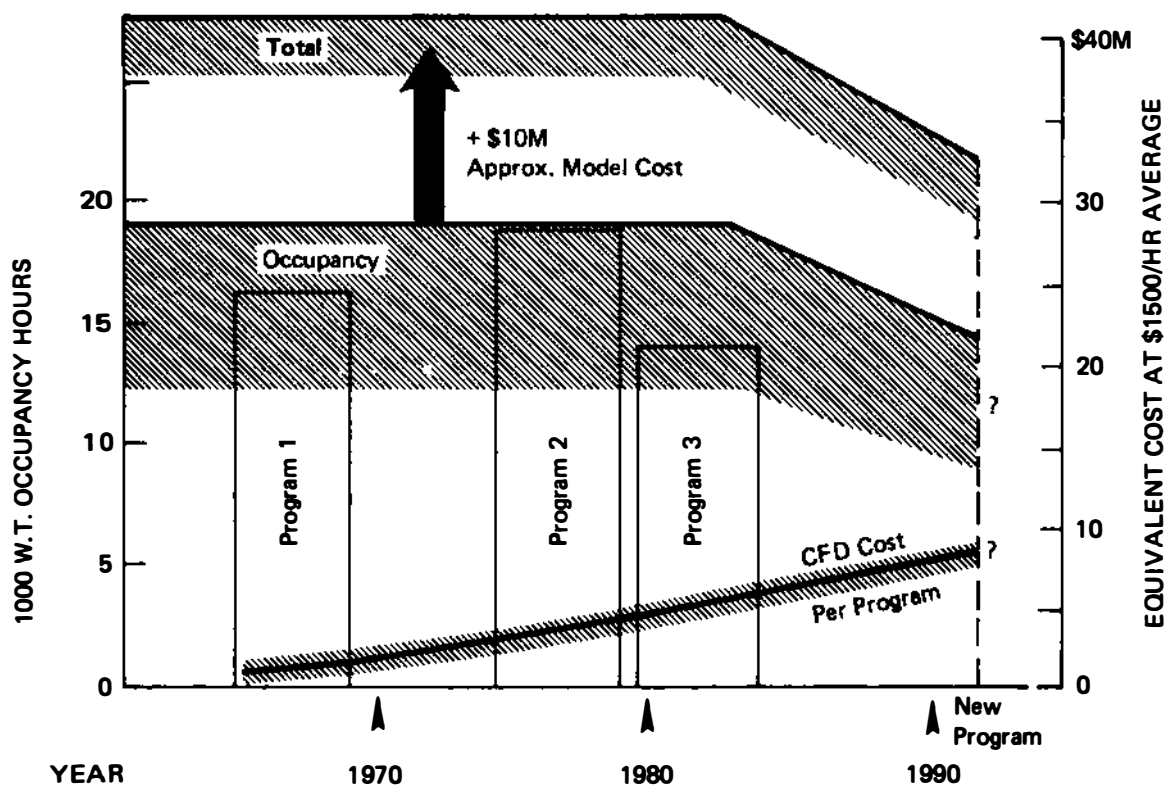
MODEL TYPE	RANGE DOLLARS	BASIC MODEL	NACELLE AND STRUT OPTIONS		FLAPS, SLATS LANDING GEAR ETC.	TOTAL MODEL COSTS
		Wing, Body, Tails, Flow Thru Nac. & Strut	Blowing Nac. and Strut	Turbo Powered Nac. and Strut		
<u>HIGH SPEED</u>						
Force Model No Static Pressures 1 Baseline Config.	Low	106,000	160,000*	80,000*		
	High	170,000	240,000*	120,000*		
Loads Model 1000 Static Pressures 1 Baseline Config.	Low	240,000	160,000*	80,000*		
	High	360,000	240,000*	120,000*		
Force 1/2 Model 200 Static Pressures 1 Baseline Config.	Low	120,000	140,000*	64,000*		
	High	180,000	210,000*	96,000*		
<u>LOW SPEED</u>						
Force Model No Static Pressures 1 Baseline Config. with 4 Sets of Flaps, Slats and Spoilers	Low	160,000	200,000*	160,000*	120,000	280,000
	High	242,000	300,000*	240,000*	180,000	422,000
Loads Model 1400 Static Pressures 1 Baseline Config. with 4 Sets of Flaps, Slats and Spoilers	Low	296,000	200,000*	160,000*	160,000	456,000
	High	444,000	300,000*	240,000*	240,000	684,000

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*Optional Costs not included in Basic Model or Total Model Costs.

TABLE 2 Continued

MODEL TYPE	RANGE DOLLARS	BASIC MODEL	NACELLE AND STRUT OPTIONS	
		Wing, Body, Tails, Flow Thru Nac. & Strut	Blowing Nac. and Strut	Turbo Powered Nac. and Strut
<u>FLUTTER</u>				
Low Speed Full Model	Low	420,000		
1 Baseline Config. with 3 Sets of Payload and Fuel Weights	High	630,000		
Transonic 1/2 Model	Low	396,000		
1 Baseline Config. with Remote Liquid Fueling Sys., 1/2 Horiz. Tail	High	594,000		



**Table 3 Wind Tunnel and CFD Costs
 Typical Commercial Transport Development Program
 (1981 Dollars)**

\$10 M over a ten-year period. Bearing in mind the inflationary forces and the uncertainties, these figures are not out of line with the 1974 estimates of Dr. Flax, given in Chapter III of this report.

Turning now to AEDC facilities, Table 4 gives approximate figures for the direct costs of operation for the most usual type of development program, a series of force and moment tests requiring 150 polars. The base costs of direct labor, materials and computer for the smaller von Karman Facility (VKF) wind tunnels as charged to a defense contractor usually through his military project office, is in line with the cost charged by NASA to commercial users for their unitary wind tunnels and also with the costs of similar wind tunnels in Table 1. The increase in these costs for the 16-ft. tunnel is to be expected in view of the increased size. The most surprising feature is the quite excessive cost of electric power.

Electric power costs have increased all over the country in the last few years; the cost of power for the NASA Ames Lab Unitary Tunnel is now about \$17 per megawatt hour, over twice the rate for the decade of the 1960s. In contrast, AEDC power cost experience reported to the committee reflects a ten-fold rise as shown in Figure 1.

In response to an enquiry by a committee member, a TVA spokesman provided the following information on power cost increases throughout the system, excluding demand charges:

1970-80	8.8% per year
1980-90	2.9% per year
Subsequent to 1990	0.4% per year

These do not explain more than a small fraction of the actual increase, implying that demand charges have been excessive. In fact, they were about 60 percent of the total power cost prior to recent renegotiations of the contract with TVA. The new contract resulted in significant reductions of the total cost of electrical power at AEDC. New contractual definitions of off- and on-peak periods, reduction of demand levels of power, and development and exploitation of new concepts called "Time of Day Rates" and "Preferred Surplus Power" were the principal factors in cost reductions. Actual cost of power for the last five months of FY 1982 averaged about \$50 per megawatt hour compared to \$70-\$80 in prior months.

The operating engineers in AEDC have taken many steps to offset this high power demand cost by increasing the productivity of the facilities. They have been able to step up the rate of taking data during air-on periods by factors of two or more. These improvements are detailed, for the PWT tunnels, in an American Institute of Aeronautics and Astronautics (AIAA) 1981 paper by R. Dean Herron (Ref. 1). Unfortunately, the conventional method of defining user costs per occupancy hour, as discussed earlier, completely masks this excellent step in improving the facility's output per dollar.

Thus, the costs of electric power in wind tunnels lie between \$17-\$18 for the Ames Unitary tunnel and \$50-61 for AEDC facilities.

TABLE 4 AEDC Wind Tunnel Test Cost Breakdown (Approximate)
 (Based on typical force test program requiring 150 polars,
 FY 1982)

	16 Ft. TRANSONIC	16 Ft. SUPERSONIC	4 Ft. TRANSONIC	VKF, A,B,C SUB- SUPER- HYPER- SONIC
PER PROGRAM:				
Polars Per Air-on Hour	6	6	7.5	15
Air-on Hours	25	25	20	10
Occupancy Hours	50	50	33	21
Energy Consumption (MWH)	4000	6000	925	950
Direct Cost* (\$1000)	450	600	150	120
PER OCCUPANCY HOUR:				
Total Direct Cost* (\$)	9000	12000	4500	3800
Labor, Materials, Computer (\$)	3000	3000	2500	1500
Power (\$)	6000	9000	2000	2300
Power, Percent of Total Direct	65%	75%	45%	60%

*Direct cost includes direct labor, materials, computer costs. It does not include capital recovery (depreciation and interest), repair and maintenance, improvement or modernization costs.

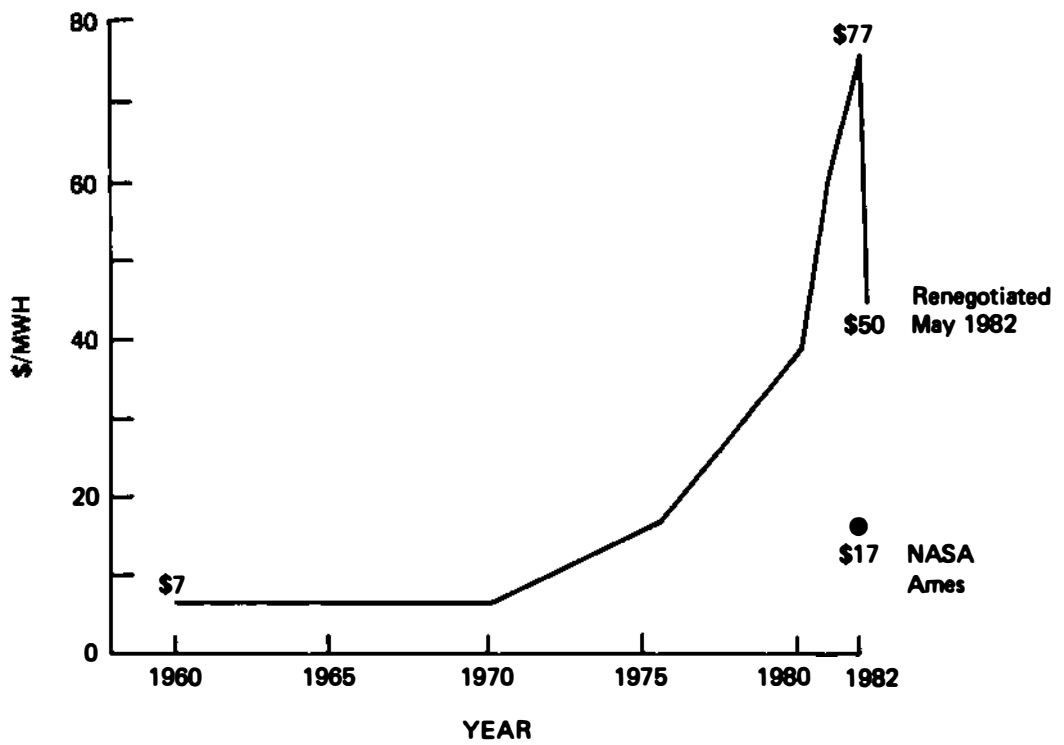


Figure 1 AEDC Power Cost.

This is illustrated in Table 5, which gives actual power costs in 1981 for a number of wind tunnels usually employed by industry in its design development.

The direct costs of operation of the major AEDC propulsion test cells are given in Table 6. They also suffer from high electric power costs; on the average, 35 to 40 percent of the total is attributable to power.

In the near future, two new facilities of great interest to the aerospace industry will start operations; the Aeropropulsion Systems Test Facility (ASTF) at AEDC and the National Transonic Facility (NTF) at NASA Langley Lab. Estimates of operating cost of the NTF, a nitrogen-cooled wind tunnel offering Reynolds' numbers up to flight values (to 80×10^6) have already been made by NASA engineers (Ref. 2) and show that the cost of liquid nitrogen coolant is the major component, reaching a maximum of \$45 per second of operation. For a typical projected test of a transonic transport aircraft model, with 142 polars, the average operating cost is roughly \$2,500 per polar, or \$6,200 per occupancy hour. Without cooling, and with a stagnation pressure of 1 atmosphere (for comparison with Table 1), the total cost would be only 20 percent of the figures.

Wind tunnels and CFD methods show a similar characteristic of increasing cost with increasing Reynolds' number. However, whereas wind tunnel costs are inflating by 5 to 10 percent per year (neglecting the anomalous AEDC data), the cost of computer operations is falling at the rate of 20 to 30 percent per year. As noted in Section II-3 of this report, for CFD applications, these gains in computer technology will be invested in higher capability at an affordable cost, for at least the next 15 years, with Stage III (Reynolds averaged Navier-Stokes) as the target for wide industry application by the end of that period. Stages I and II are already in use in industry, and the CFD cost curve in Table 3 is a very rough estimate of the costs incurred by Boeing to date, with its probable projection as Stage III is introduced.

In view of the rapidity of computer development, the computer will probably be rented, and Figure 1, Section II-3 suggests a monthly rental cost of \$300,000 to \$600,000. This machine in the late 1980s will probably have a memory of 100 to 200 million words, sufficient to map a complete aircraft (2 to 9 million grid points) with 20 to 30 words per grid point. The most difficult element in the estimation of CFD operating cost is the evaluation of software requirements. Branscomb (Ref. 3) states that software costs will ultimately rise to 85 percent of the total. As discussed in Section 1, however, the CFD function merges with the entire task of aerodynamic design, and the problem is to identify and separate those functions which are specifically needed for CFD programming--liaison with CFD research teams, selection of suitable programs, establishing appropriate grid systems, etc. A rough order-of-magnitude estimate suggests that this software will be as much as the rental cost, so that the major aerospace company will be spending \$600,000 to \$1.2 M per month for its CFD capability within 15 years.

TABLE 5 Power Rates and Total Power Used for Various Facilities in FY 1981

	\$/MEGAWATT-HOUR	1000 MEGAWATT-HOURS USED
AMES	18.4	195.5
LANGLEY	30.4	137.9
JOHNSON	37.9	146.4
LEWIS	39.0	161.2
MARSHALL	41.4	96.5
GODDARD	45.2	91.5
MICHOUD	47.5	79.3
KENNEDY	48.0	181.6
DOWNEY	59.1	102.2
JPL	59.7	67.6
AEDC	61.0	

TABLE 6 AEDC Propulsion Test Costs (FY 1982)--Direct Labor, Power, Fuel, and Computer

TEST CELLS	PER ENGINE RUNNING POWER
T1, T2, T4	\$ 8,000 - \$10,000 per engine hour
J1, J2	\$12,000 - \$15,000 per engine hour
T5	\$ 5,000 - \$ 7,000 per engine hour
ASTF	Comparable to J1, J2

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