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NASA CFD VALIDATION WORKSHOP

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NASA Ames Research Center
July 14 - 16, 1987

NASA CFD VALIDATION WORKSHOP

NASA AMES RESEARCH CENTER
MOFFETT FIELD, CA 94035

JULY 14-16, 1987

JOSEPH G. MARVIN, CHAIRMAN

NASA CFD VALIDATION WORKSHOP
Ames Research Center

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I. WORKSHOP SUMMARY

WORKSHOP SUMMARY

The first NASA CFD Validation workshop was held at the Ames Research Center on July 14-16, 1987 with 108 persons in attendance. After being welcomed by the Director of the Office of Aerophysics at the Ames Research Center, NASA Headquarters management presented introductory comments and expectations for the meeting. Recommendations from a recent review of CFD validation activities at three NASA Research Centers, conducted by the Ad Hoc Committee on CFD Validation of the Aeronautics Advisory Committee (AAC), were presented. Definitions developed by the Committee for code verification, code calibration and corresponding experiments were also introduced and discussed. NASA will use these definitions in conjunction with the CFD Validation program as a tool to manage and maintain a balanced program. For completeness, a copy of the AAC Ad Hoc Committee report is included herein.

The Ames, Langley, and Lewis Research Centers presented overviews of their CFD Validation activities with brief descriptions of their key experiments. These presentations covered the entire speed range and included external and internal aerodynamic flows, combustion, aerothermal loads, and aeroelasticity. Following the NASA presentations, other government installations, industry, and universities presented overviews of their CFD Validation activities and needs. The presentations and speakers are listed in the Workshop Program which is included herein along with copies of the presentations.

After these formal presentations, the workshop attendees were divided into six working groups. The working groups focused on the following key areas: Low Speed Aerodynamic Flows; High Speed Aerodynamic Flows-Commercial; High Speed Aerodynamic Flows-Military; Internal Flows; Hypersonics-Chemically Reacting External/Internal Flows; and Hypersonics-External Aerothermodynamics. Each working group was given a list of five issues to address in their discussions. The issues were: (1) identify key efforts (numerical and experimental) required to meet immediate modeling and validation needs; (2) identify near-term and far-term critical problem areas that require new or additional modeling and validation activities; (3) identify computational, experimental, facility and instrumentation, or other capabilities required to investigate these critical problem areas; (4) identify key modeling and validation projects that are potential cooperative/joint ventures; and (5) define, identify and/or propose standardized test cases for modeling and validation.

The working groups met for about 6 hours to discuss these issues and prepare summaries.

The formal workshop resumed with the various spokespersons presenting the results from their group discussions. These presentations have also been included herein. Several common recommendations were made. These, not in priority order, included: (1) provide closer cooperation between CFD developers and experimentalists at the outset of verification projects with a lasting commitment from both to see the projects through to completion; (2) provide detailed measurements of the flow field and boundary conditions in addition to model surface measurements and integral quantities; (3) provide improved or new non-intrusive measurement capabilities, especially for

hypersonic or reacting flow conditions; (4) provide redundancy in both measurements and experiments whenever practical so as to clarify data accuracy and credibility; (5) provide dedicated large facilities for validation research and increase flight-based research activities; and (6) provide standardized test cases with accessible electronic data bases. The recommendation for standardized test cases received a strong consensus during the workshop. NASA will review the recommendations from the groups and determine a course of action to advocate their implementation.

The workshop concluded with the general feeling that the meeting was very successful. Attendees from the various research centers, universities and industry expressed a renewed understanding of each other's viewpoints on CFD validation. Experts in computational and experimental fluid dynamics were able to begin the synergistic interaction critical to successful validation activities in their one-on-one discussions. Many felt that this workshop should be the forerunner of future workshops on specific topic areas because the workshop atmosphere provides a forum for discussing both successes and failures which taken together often lead to more expeditious problem solutions.

II. AD HOC COMMITTEE REPORT

COMPUTATIONAL FLUID DYNAMICS VALIDATION

Prepared for

NASA'S AERONAUTICS ADVISORY COMMITTEE

by

THE AD HOC COMMITTEE ON CFD VALIDATION
OF THE AERONAUTICS ADVISORY COMMITTEE

May 1, 1987

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INTRODUCTION AND APPROACH

Computational Fluid Dynamics (CFD) is becoming an increasingly powerful tool in the aerodynamic design of aerospace systems, owing to improvements in numerical algorithms, geometric modeling, grid generation, and physical parameter modeling, as well as dramatic improvements in supercomputer processing speed and memory. With the realization of the potential of forthcoming supercomputers, much of the current CFD work will be expanded to address more complex configurations, geometries, flight regimes, and applications, while some of the existing work will become components of more complex systems of solutions to problems of modeling, grid generation, flow field solvers, and flow visualization. Thus, CFD will become an important aerospace design and development tool requiring a high level of confidence.

To meet the required confidence level, the existing and forthcoming CFD application codes must be verified and validated with the best available experimental data. Because of the complexity of the aerodynamic flows that will be routinely computed, the experimental data base must be expanded to include not only surface-measurable quantities, but also detailed measurements of fluid and thermal parameters throughout the flow region of interest. These focused experimental tests clearly require detailed flow quantity measurements in addition to integral checks. Also, the errors inherent in experimental testing must be identified, understood, and minimized in order to produce the high-quality, accurate benchmark data sets that are required for validation of complex CFD applications codes and for use in developing physical modeling data for complex flows.

NASA's Aeronautics Advisory Committee formed an Ad Hoc Committee to review the CFD validation activities at three NASA research centers in order to assess the current and planned research programs. The Committee membership was selected from the Aeronautics Advisory Committee and the ARTS (Aerospace Research & Technology Subcommittee) and SSTAC (Space Systems Technology Advisory Committee). The members and the Liaison Representatives from each center are listed in Appendix A.

The specific charge to the Subcommittee is as follows:

1. Review the NASA Program at the three research centers. The purpose of review is to

   - Classify CFD research to identify and characterize verification needs.

   - Assess ongoing and planned CFD verification experiments.

The scope includes application code development and associated verification experiments in the following areas:

- Internal and external aerodynamics across the speed range.
- Combustion and chemical kinetics.
- Aerothermodynamics.
- Physical parameter modeling (e.g., turbulence, transport properties, etc.)

Specific attention is to be given to requirements/needs in areas of future applications for vehicle design and development. Utilize results of the NRC study on CFD capabilities where applicable.

2. Identify concerns and recommend changes, as appropriate, in the following areas:

   - Scope, pace, and quality of experiments.
   - Instrumentation adequacy/accuracy.
   - Facility adequacy (flow quality).
   - Criteria and techniques for using data to validate CFD codes.
   - Staffing adequacy.

The committee held five meetings, as follows:

23 September 1986 - General Dynamics, Fort Worth Division

13-14 November 1986 - NASA Langley Research Center, Virginia

8-9 January 1987 - NASA Ames Research Center, California

12-13 February 1987 - NASA Lewis Research Center, Ohio

19 March 1987 - NASA Headquarters, Washington DC

The first meeting in Fort Worth was held to interpret the charter and formulate the approach to be followed when reviewing the centers. As a result, a set of specific questions were developed to aid in assessing the validation projects. These questions were supplied to each of the three Centers before the committee's visit in order to focus the presentations on specific issues of concern and to provide the committee with a consistent

basis for evaluating the validation projects. The question set is given in Appendix B for reference.

Reviews at each of the three NASA research centers consisted of one day of presentations by center management and individual researchers involved in CFD and related experimentation, followed by a one-half day executive session in which the presented material was reviewed to arrive at appropriate conclusions. The executive sessions were attended by center management as their schedules permitted.

From the outset, the committee was aware that time would not permit an in-depth evaluation of each validation project. It was thus decided that the assessment would be a top-level review of the overall NASA activities in CFD validation, with attention given to the specific elements given in the charge. The following sections present the results of this assessment, including specific conclusions and recommendations.

The Committee would like to express its appreciation to the three NASA centers for their excellent response to the committee's inquiry. The outstanding effort made by the individual presenters is a credit to NASA. Special thanks are given to each liaison representative for coordinating the center visits and contributing to the discussions.

CFD RELATED EXPERIMENTS

CFD has opened a new realm of capability for fluid dynamicists in that, for the first time in history, the intricate features of complex flows can be computed. This unique capability in turn sets the stage for new levels of understanding of fluid flows, once the researcher or designer is satisfied that the code's numerical algorithms and physical parameter modeling accurately represent the critical physics of the flow. This confidence in CFD can only be gained by detailed comparisons with experimental data of sufficient accuracy and detail to verify the CFD capability.

In order to distinguish the unique characteristics of experimental studies required for CFD validation, the committee has developed the following definitions:

> CFD Code Validation - Detailed surface-and-flow-field comparisons with experimental data to verify the code's ability to accurately model the critical physics of the flow. Validation can occur only when the accuracy and limitations of the experimental data are known and thoroughly understood and when the accuracy and limitations of the code's numerical algorithms, grid-density effects, and physical basis are equally known and understood over a range of specified parameters.
>
> CFD Validation Experiment - An experiment that is designed to provide detailed building block data for developing and validating CFD codes. This objective requires that the data be taken in the form and detail consistent with CFD modeling requirements and that the accuracy and limitations of the experimental data be thoroughly understood and documented.
>
> Validated CFD Code - A code whose accuracy and range of validity has been determined by detailed comparison with CFD validation experiments, so that it can be applied, without calibration, directly to a geometry and flow condition of engineering interest with a high degree of confidence.
>
> CFD Code Calibration - The comparison of CFD code results with experimental data for realistic geometries that are similar to the ones of design interest, made in order to provide a measure of the code's ability to predict specific parameters that are of importance to the design objectives without necessarily verifying that all the features of the flow are correctly modeled.

Calibration of analytical results has been the mainstay of the Aerospace Industry. Because of past limitations and simplifying assumptions inherent in calculations, the designer has relied upon correlations with limited experimental data to gain confidence in and provide correction factors for analytical applications. Calibration continues to play an important role in the application of CFD to engineering design, especially for less mature codes that have not been fully validated.

Four categories of experimentation are recognized to be intimately associated with the development of CFD capability:

A. Experiments designed to <u>understand flow physics</u>.

B. Experiments designed to <u>develop physical models</u> for CFD codes.

C. Experiments designed to <u>calibrate</u> CFD codes.

D. Experiments designed to <u>validate</u> CFD codes.

All four categories of experiments are important and are necessary to build a mature CFD capability. Validation experiments should be only a part of total experimental focus of NASA and should be formulated to provide specific data for validating CFD codes.

3
CENTER REVIEWS

Many excellent experimental programs are being conducted at Langley, Ames, and Lewis. Many of these experiments fall into the four categories, A-D, listed in the previous section. It is evident from the reviews that CFD validation is a relatively new concept and that each center is attempting to meet the requirements primarily by merging ongoing testing with CFD code development. A number of building-block experiments have been initiated to provide requisite data for validation, and some interesting projects are in progress. In many cases, however, these are generic experiments. They are not closely coupled to any code.

Because of the dearth of projects considered to be true CFD validation efforts, the committee could not provide an in-depth evaluation of the scope, pace, and quality of experiments or of the staffing adequacy as given in the charter. Instead efforts were directed toward defining the unique requirements that distinguish validation from other CFD-related experimentation.

A total of 45 projects were selected by NASA for review at the three research centers. Although all of the projects were presented as CFD-validation experiments, only a few were considered by the committee to be true validation experiments in accordance with the definition given in the previous section. The work presented covered a wide range of experimental and CFD programs that seemed to be somewhat randomly selected from many ongoing and planned NASA projects. Some had been in progress for many years; others had been put together in an obvious attempt to build support for future funding. Some projects were tied to existing CFD codes, and some relied on codes yet to be developed. In many cases, the relationship of the experiments to specific CFD requirements was obscure. Some of the projects came close to the requirements for validation and, with attention to CFD details and/or experimental measurement requirements, could be useful validation projects. A large number of the projects were judged to be of the code calibration variety.

Each of the centers elected a slightly different approach for the CFD validation review.

<u>Langley Research Center</u>: Most of the projects that were presented were ongoing and not initially designed as validation studies. The Committee recognizes that some building-block experiments and more fundamental computational studies relating to turbulence modeling and transition were not presented. Therefore it was not possible to assess these as possible validation projects. Three projects that might be used as prototypes for CFD validation at subsonic, tran-

sonic, and hypersonic speeds are the Kjelgaard, Putnam and Gnoffo studies, respectively. The codes to be validated were clearly identified and the experiments were carefully chosen. Some of the other projects had good elements, but the coupling between the experiments and the codes was weak or the definition of the validation experiments or code was not well-defined. Many of these projects belonged to categories A-C.

Ames Research Center: The emphasis here is more on building-block experiments and the understanding of some of the basic flow physics, in particular, turbulence modeling. The projects of Kim/Robinson, Brown/Horstman, Kussoy/Horstman and Erickson/Hicks for low-speed, supersonic, hypersonic and vortical flows, respectively, appear to be among the promising validation studies. Questions of flow unsteadiness, three-dimensionality, turbulence modeling at high-speeds, and the validity of the Euler system for vortex-dominated flows are to be addressed with these validation projects. There is considerable emphasis on direct Navier-Stokes solvers and Large Eddy Simulation. At this time, true validation of these codes depends upon increased computer capability and/or experiments designed to cover the very low Mach and Reynolds number range for which current computations are possible. These current studies represent numerical experiments to provide data for turbulence modeling and are extremely valuable. The relation of the Parabolized Navier-Stokes, Thin Layer Navier-Stokes, Turbulence Averaged Navier-Stokes, and Direct Navier-Stokes studies to similar projects at the other NASA centers should be clarified. Closer coordination between centers could further strengthen these validation requirements.

Lewis Research Center: The emphasis here is on averaged Navier-Stokes methods for internal duct and turbomachinery flows. Some excellent data bases are being developed from the experimental programs. The projects of Strazisar and Simoneau are particularly noteworthy. Almost all of the CFD validation is focused on two codes (RCV3D and PROTEUS) and both are only in the developmental stage. The user friendly adaptability aspects of the PROTEUS code are potentially very positive, but we were not provided with any details concerning the code development and the range of applicability for CFD validation. The relationship of RCV3D to other TLNS codes was not provided and the coupling between the tests and CFD was not clear. The time/space averaging analysis presented by Adamczyk and the related experiments by Hathaway represent a novel approach to develop a code for multistage blade row interactions. Although this project does not yet represent a CFD validation study, it is one of the few projects in which the tests are to play a role in the modeling of the physics. Some of the important flow physics associated with internal flows were not emphasized

in the CFD validation studies presented during the review, viz., transition, turbulence modeling, unsteady behavior.

With few exceptions, each center has targeted parabolized, thin-layer, time-averaged, and direct Navier-Stokes code development for their future validation studies. Inviscid and interacting boundary layer codes were discussed for airfoil, propeller, and rotor design and for vortical flows. Although they do not model all of the flow physics associated with certain strong-interaction and/or three-dimensional problems, they do model the critical physics for many flows. Therefore, codes other than averaged or full Navier-Stokes codes should still be validated for some range of geometries and flow parameters. Emphasis on this class of codes was minimal.

Although there has been some effort to coordinate the activities of the experimenters and the code developers, this interaction is restricted by the limitations of the facilities, physical models, and computers. Therefore, it is reasonable to conclude that only a few of the projects presented during the center reviews or to be proposed in future years can be suitable for CFD validation. In this regard, in order to satisfy the definition of code validation proposed by the committee, it is necessary to match the capabilities of the codes with those of the facilities, e.g., unsteadiness, three-dimensionality, transition, and turbulence modeling for separated, three-dimensional, and high speed flows.

Some duplication for a given set of computations and experimental measurement is desirable. It would allow for comparisons of artificial viscosity, grid dependency of different codes, different turbulence models, and different experimental techniques. Closer coordination between centers could further strengthen these validation requirements.

FACILITIES AND MEASUREMENTS

The Committee observed that CFD validation is severely hampered in some areas by the lack of critical measurements obtained under realistic conditions. The problem is particularly critical at high Mach numbers where the viscous inviscid three-dimensional problems are further complicated by real-gas effects, but, many problems in the lower Mach number range which are also not adequately covered.

To provide the basis for CFD validation, the experiments must provide measurements, with adequate accuracy and resolution, under conditions of Mach number, Reynolds numbers, noise, and turbulence, which are representative of the conditions that CFD will be used to predict. The range of the experiments must extend from simple basic ones to those covering conditions of flight. They must be adequate to test CFD in a multi-dimensional environment with redundant instruments, providing clear indications of what is needed to evaluate CFD's ability to predict details as well as trends and to explore boundaries of the range of application for specific codes or classes of codes.

At lower Mach numbers, subsonic facilities seem to be adequate and the measurements are possible, but not usually available in sufficient detail or accuracy. At high Mach numbers, the tunnels are much less capable of fully simulating Mach number, Reynolds number, turbulence, real gas effects, combustion. The realism of their simulation of flight is questionable for some phenomenon such as transition and combustion. Direct links between high-speed wind tunnels and flight are not usually available, although they are definitely within reach and are an important connection in the test of CFD against realistic flight environments - the ultimate application of CFD. Specific instrumentation and facilities needed for the special measurements required to validate codes must be developed when the state of the art is inadequate. The phenomena of transition, turbulent flows, unsteady flows, real gas effects, and "hot section" (combustion) propulsion systems are all very important phenomena where the facilities and measurements limit the ultimate application, with confidence, of CFD techniques.

CONCLUSIONS

Many excellent experimental programs are being conducted at the NASA research centers. The programs are generally attacking pertinent problems. However, only a few of the projects reviewed were considered by the committee to be CFD-validation projects. Further, adequate coordination among NASA centers was not evidenced in the reviews.

CFD validation is a relatively new concept that requires clearly defined and disciplined coupling between CFD and experiments. The committee has proposed the following definition of CFD validation, which emphasizes the computational and experimental discipline required and distinguishes validation from other experimentation related to CFD:

> CFD Code Validation - Detailed surface- and flow-field comparisons with experimental data to verify the code's ability to accurately model the critical physics of the flow. Validation can occur only when the accuracy and limitations of the experimental data are known and thoroughly understood and when the accuracy and limitations of the code's numerical algorithms, grid-density effects, and physical basis are equally known and understood over a range of specified parameters.

The committee recognizes that four categories of experimentation are required for developing CFD capability:

A. Experiments designed to understand flow physics.

B. Experiments designed to develop physical models for CFD codes.

C. Experiments designed to calibrate CFD codes.

D. Experiments designed to validate CFD codes.

All four categories of tests are important and are necessary to build a mature CFD capability. Validation tests should be only a part of total test focus of NASA and should be formulated to provide specific data for validating CFD codes.

CFD validation is severely hampered in some areas by the lack of critical measurements under realistic conditions-especially at high Mach numbers. Measurements must be taken with adequate accuracy and resolution, and with redundant instruments, in order to evaluate CFD's capability to predict details and trends as well as to explore boundaries of application for specific codes. Specific instrumentation and facilities need to

be developed when the state of the art is inadequate.

Equally important for validation is the mapping of the CFD code's sensitivity to numerical algorithms, grid density, and physical models. These effects must be known to the same degree as the experimental accuracy and resolution in order to understand the applicability of the code over a range of flow parameters.

RECOMMENDATIONS

It is recommended that

1. NASA classify its CFD related experiments into the above-defined categories A, B, C, and D. The classification provides a framework for future evaluation and allocation of resources.

2. NASA adopt a sharply defined program plan for CFD validation, consistent with the definitions proposed by the Committee in this report. In particular,

   - Projects falling under this program should be closely coordinated and adequately funded.

   - The limitations of the facilities, instrumentation, proposed models, and codes should be clearly specified at the onset of the projects, as should the critical data set required and the range of validity of the modeling assumptions.

   - The questions of such phenomenon as unsteadiness, three-dimensionality, transition, turbulence models, and the applicability of inviscid/interacting-viscous/Navier-Stokes models should influence the choices of experiments, code development, and application.

   - Duplication of experiments and code development should involve several centers.

   - A validated code should become a NASA or general code, not merely the code of a given center.

3. NASA pay careful attention to the instrumentation and facilities required to provide data of adequate accuracy and in the form and detail required for CFD validation. Close coordination must be maintained between centers.

4. NASA establish a Coordinating Board for CFD validation, consisting of key project leaders from each of the three NASA centers and chaired by NASA Headquarters. This board should have responsibility for defining, coordinating, and focusing the CFD validation effort.

APPENDIX A

COMMITTEE ON CFD VALIDATION MEMBERSHIP

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APPENDIX B

CFD VALIDATION ACTIVITY QUESTIONS

Objective:

- What are the specific objectives of the experiment relative to the CFD code?

Scope:

- What is the application being addresed by the Code?
- Why was this code selected?
- What is the domain of validation?
- What experiments are required for validation?

CFD Drivers:

- What are the physical modeling assumptions?
- What are the numerical modeling assumptions?
- What are the geometric/grid generation assumptions (degree of complexity)?
- What is the code's recognized limitation?

Experimental Approach:

- What data are required to validate the codes?
- What data will be taken?
- What instrumentation will be used, is it adequate for validation?
- What are the limitations of the instrumentation?
- What facilities are required?
- What facilities will actually be used?
- What are the facility limitations, range and characteristics?

Assessment:

- How will you evaluate your results?
- What re the uncertainties?
- What is the criteria for measurement of success?

Staffing:

- What is the manpower level assigned to this activity?
- Who are the researchers?

Pace:

- What is the relative pace of the CFD and validation experiments?
- What is the level of effort, $?
- What is the schedule and important milestones?

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IV. WORKSHOP PROGRAM

NASA CFD VALIDATION WORKSHOP
Ames Research Center
Space Science Auditorium, Bldg. 245

PROGRAM

Tuesday, July 14, 1987

7:15-8:15 a.m.	**Registration and Distribution of Conference Materials: Visitors Center and Bldg 245**

OPENING

8:30 a.m.	**Welcome** V. L. Peterson, NASA, Ames Research Center
8:40 a.m.	**Workshop Format** J. G. Marvin, NASA, Ames Research Center
8:45 a.m.	**NASA-Headquarters Remarks** R. A. Graves, NASA, Headquarters

AMES RESEARCH CENTER PRESENTATIONS

9:10 a.m.	**Status and Needs of CFD Code Validation** T. L. Holst, NASA, Ames Research Center
9:35 a.m.	**Experimental Fluid Dynamics. Part I - Brief Overview. Part II - Flow Modeling and Verification Experiments - RF Division** J. G. Marvin, NASA, Ames Research Center
10:00 a.m.	**Flow Physics Experiments- RF Division** S. S. Davis, NASA, Ames Research Center
10:25 a.m.	Break
10:40 a.m.	**Fighter-Like Vortical Flow Experiments - RA Division** L. L. Erickson, NASA, Ames Research Center
11:00 a.m.	**Hypersonics Flow Code Validation Activity - Real Gas Flows - RT Division** G. S. Deiwert, NASA, Ames Research Center

NASA, LANGLEY RESEARCH CENTER PRESENTATIONS

11:25 a.m.	**A Review of Transonic Code Validation Research Activities** P. J. Bobbitt, NASA, Langley Research Center
11:55 a.m.	**Low Speed Code Validation Activities** J. C. South, Jr., NASA, Langley Research Center
12:10 p.m.	Lunch

NASA CFD VALIDATION WORKSHOP
Ames Research Center
Space Science Auditorium, Bldg. 245

PROGRAM

Tuesday, July 14, 1987

NASA, LANGLEY RESEARCH CENTER PRESENTATIONS - (Continued)

1:25 p.m. **High Speed Code Validation**
R. W. Barnwell, NASA, Langley Research Center

1:45 p.m. **Overview of Hypersonic CFD Validation Experiments**
C. G. Miller, NASA, Langley Research Center

2:10 p.m. **High Enthalpy Aerothermal Loads**
A. R. Wieting, NASA, Langley Research Center

2:25 p.m. **Validation of Computational Aeroelasticity**
W. Whitlow, Jr., NASA, Langley Research Center

2:40 p.m. Break

NASA, LEWIS RESEARCH CENTER PRESENTATIONS

2:55 p.m. **Overview of the Lewis Experimental Program**
L. A. Povinelli, NASA, Lewis Research Center

3:15 p.m. **3-Dimensional Unsteady Flows in Multistage Turbomachinery**
M. D. Hathaway, NASA, Lewis Research Center

3:35 p.m. **Separation in Low Speed Duct Flows**
B. H. Anderson, NASA, Lewis Research Center

3:55 p.m. **Separation in High Speed Duct Flows**
B. H. Anderson , NASA, Lewis Research Center

4:15 p.m. **Heat Transfer in 3-D Flow Regions Generated by Intersecting Surfaces**
R. E. Gaugler, NASA, Lewis Research Center

4:35 p.m. **Planar Compressible Reacting Shear Layer Emphasizing Pressure Wave - Shear Layer Interaction**
E. Mularz, NASA, Lewis Research Center

OTHER GOVERNMENT LABORATORY PRESENTATIONS

4:55 p.m. **AFWAL Efforts in Code Validation and Perspective on Experiments**
R. Neumann and M. Buck, AFWAL/FIMG

6:00 p.m. Social Hour - Cash Bar, Officers Club
Hors d'oeuvres

NASA CFD VALIDATION WORKSHOP
Ames Research Center
Space Science Auditorium, Bldg. 245

PROGRAM

Wednesday, July 15, 1987

Bldg. 245

OTHER GOVERNMENT LABORATORY PRESENTATIONS (Continued)

8:00 a.m. **Base Flow CFD Needs: BRL**
C. J. Nietubicz, US Army Ballistics Research Lab

INDUSTRY PRESENTATIONS

8:15 a.m. **Remarks on CFD Validation - A Boeing Perspective**
I. E. Vas, Boeing Military Airplane Company

8:40 a.m. **CFD Validation, Lockheed-Georgia**
J. B. Malone, Lockheed-Georgia Co.

9:05 a.m. **CFD Validation - McDonnell Douglas**
A. Verhoff, McDonnell Aircraft Co.

9:30 a.m. **General Dynamics Perspective on CFD Code Calibration/Validation**
I. C. Bhateley, General Dynamics

9:55 a.m. **CFD Validation Needs for Advanced Concepts - Northrop**
M. W. George, Northrop Corporation

10:15 a.m. Break

10:30 a.m. **Effects of transition on Steady and Unsteady Aerodynamics**
L. Ericsson, Lockheed Missiles and Space Company

10:50 a.m. **CFD Validation Experiments at UTRC**
W. Patrick, United Technology Research Center

11:15 a.m. **Allison Turbomachinery CFD Code Validation: Current Activities and Future Needs**
H. C. Mongia and R. Delaney, Allison Gas Turbine Division, General Motors Corp.

11:40 a.m. Lunch

NASA CFD VALIDATION WORKSHOP
Ames Research Center
Space Science Auditorium, Bldg. 245

PROGRAM

Wednesday, July 15, 1987
(Continued)

UNIVERSITY PRESENTATIONS

12:40 p.m. **Verification of 3-D Viscous Turbulent Codes for Internal Flows**
B. Lakshminarayana, Pennyslvania State University

1:05 p.m. **University of Washington Experiments**
F. B. Gessner, University of Washington

1:25 p.m. **Comments on Useful vs. Unproductive CFD Validation Experiments**
G. S. Settles, Penn State University

1:45 p.m. **Requirements for CFD Validation Experiments**
S. M. Bogdonoff, Princeton University

2:10 p.m. **NASA/University of Virginia CFD Validation Program: Transverse Jet in Combustor**
J. G. McDaniel, University of Virginia

SMALL GROUP DISCUSSIONS

2:30 p.m. **Instructions for Small Group Discussions**
J. G. Marvin, Ames Research Center

2:45 p.m. Break

3:00- 5:30 p.m. **Small Group Discussion (Various Locations to be Announced)**

Thursday, July 16, 1987

SMALL GROUP DISCUSSIONS (Continued)

Various Locations

8:00 a.m. - 12 p.m.

12:00 p.m. Lunch

FEEDBACK SESSION AND DISCUSSION

Bldg 245

1:00-4:30 p.m. Group Spokesmen

V. WORKSHOP PRESENTATIONS

WELCOMING REMARKS

FIRST NASA WORKSHOP ON CFD VALIDATION
JULY 14, 1987

VICTOR L. PETERSON
DIRECTOR OF AEROPHYSICS
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TEST FACILITY UPDATE

- FLUID MECHANICS LABORATORY DEDICATED – NOV. 1986
- 3.5–FOOT HYPERSONIC WIND TUNNEL REACTIVATED – DEC. 1986
- NAS CAPABILITY DEDICATED – MARCH 1987
- 40 X 80 WIND TUNNEL ACTIVATED – JUNE 1987
- 80 X 120 WIND TUNNEL TO BE DEDICATED – DECEMBER 1987
- 12–FOOT WIND TUNNEL RESTORATION APPROVED 1987

CENTER FOR TURBULENCE RESEARCH

WHY THE CENTER WAS FORMED

- THE TIME IS RIGHT:

  COMPUTATIONAL TECHNOLOGIES ARE MATURING: TURBULENCE CAN BE COMPUTED FROM FIRST PRINCIPLES

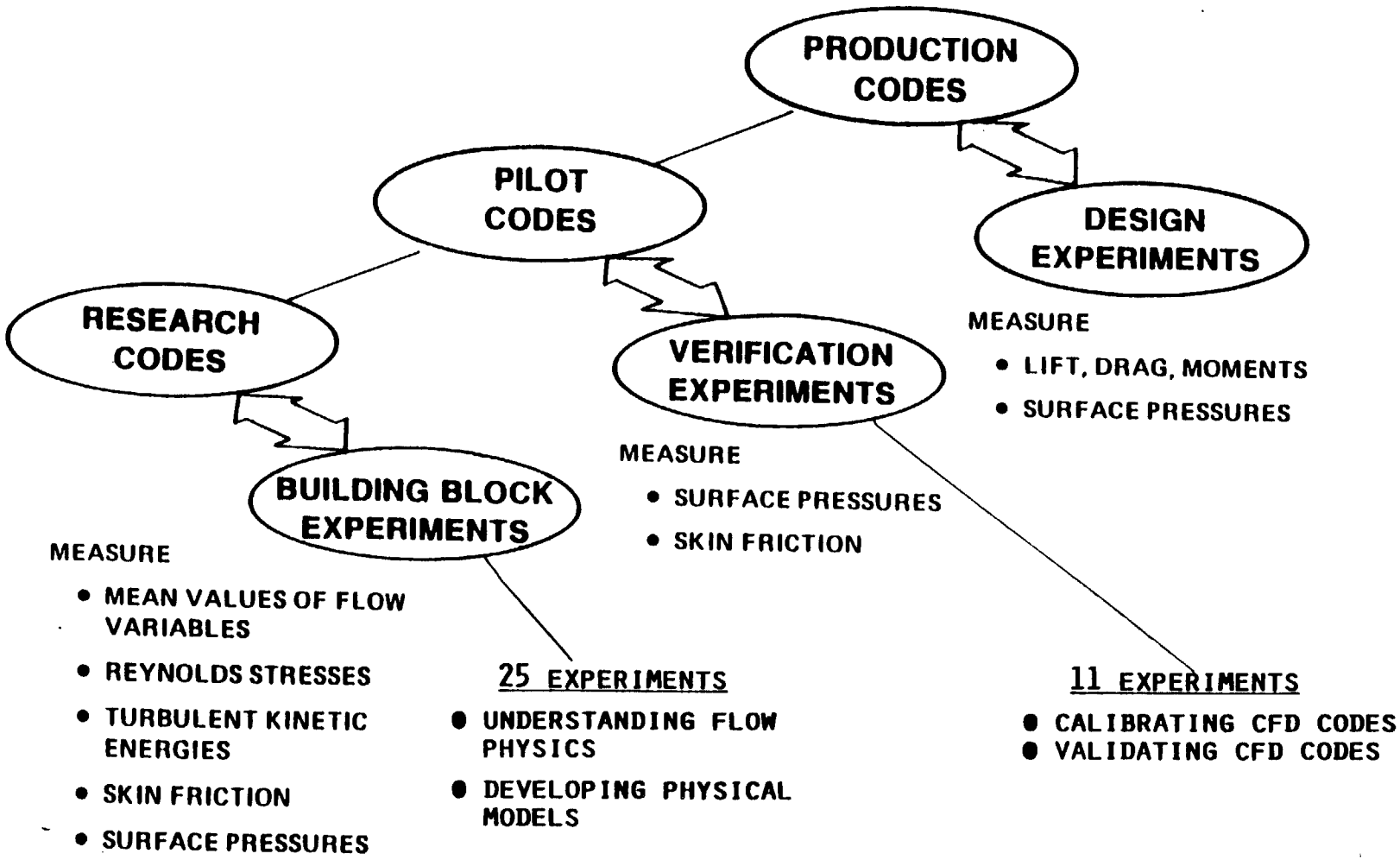
  EXPERIMENTAL TECHNOLOGIES HAVE ADVANCED: NON-INTRUSIVE MEASUREMENT METHODOLOGY, AND HIGH-SPEED DATA ACQUISITION AND PROCESSING TECHNIQUES

  THEORETICAL IDEAS ARE AVAILABLE: DYNAMICAL SYSTEM THEORY, CHAOS, FRACTALS, RNG, ETC.

- A NEW APPROACH WAS NEEDED:
  - CENTER WILL PROVIDE A CRITICAL MASS OF COORDINATED COMPUTATIONAL, EXPERIMENTAL AND THEORETICAL RESEARCH
  - CENTER WILL PROVIDE AN ENVIRONMENT CONDUCIVE TO ATTRACTING THE MOST CAPABLE PEOPLE TO CONDUCT HIGH-QUALITY SYNERGISTIC RESEARCH

FLUID DYNAMICS

INTERRELATIONSHIP BETWEEN COMPUTATION AND MEASUREMENT

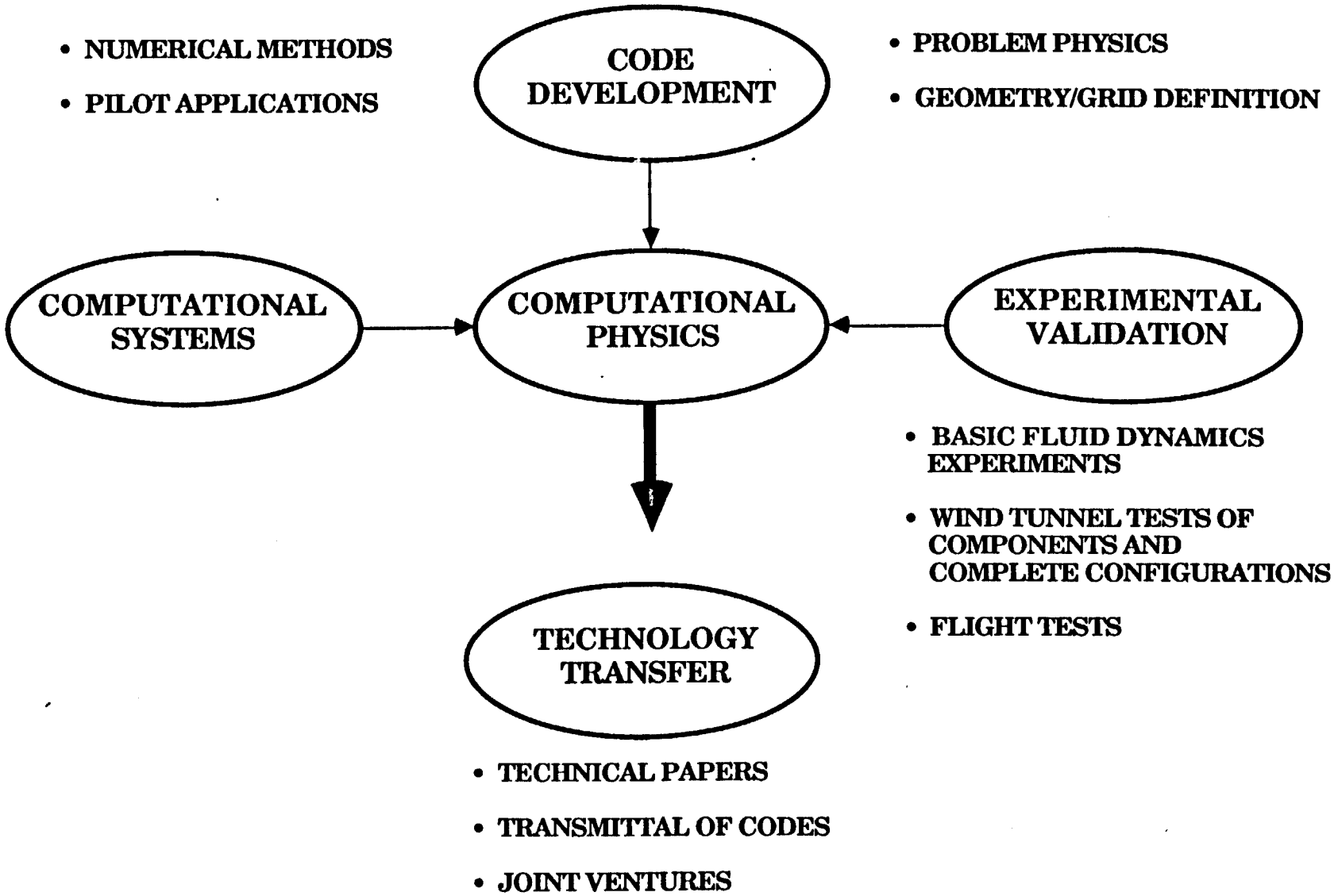


- TOTAL OF 26 ON-GOING EXPERIMENTS AT AMES

EVOLUTION OF CFD VALIDATION PROGRAM

• NEW RTOP ELEMENT, FLOW MODELING AND VERIFICATION, CREATED	FY 1986
• NRC ASEB REVIEW OF CFD ACTIVITIES	FY 1986
• NASA REVIEW AND DEVELOPMENT OF IMPLEMENTATION PLAN FOR CFD VALIDATION	FEB., 1986
• AAC AD HOC SUBCOMMITTEE REVIEW OF CFD VALIDATION	FY 1987
• NASA COORDINATING BOARD FOR CFD VALIDATION FORMED	JUNE, 1987
• NASA CFD VALIDATION WORKSHOP	JULY, 1987
• IMPLEMENTATION PLAN REVISED BY COORDINATING BOARD	AUG., 1987
• CFD VALIDATION ACTIVITIES AND IMPLEMENTATION PLAN REVIEW	SUMMER, 1988

ELEMENTS OF COMPUTATIONAL PHYSICS



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ROBERT E. WHITEHEAD	OFFICE OF NAVAL RESEARCH
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CFD CODE VALIDATION DEFINITION

- DETAILED SURFACE-AND-FLOW-FIELD COMPARISONS WITH EXPERIMENTAL DATA TO VERIFY THE CODE'S ABILITY TO ACCURATELY MODEL THE CRITICAL PHYSICS OF THE FLOW. VALIDATION CAN OCCUR ONLY WHEN THE ACCURACY AND LIMITATIONS OF THE EXPERIMENTAL DATA ARE KNOWN AND THROUGHLY UNDERSTOOD AND WHEN THE ACCURACY AND LIMITATIONS OF THE CODE'S NUMERICAL ALGORITHMS, GIRD-DENSITY EFFECTS, AND PHYSICAL BASIS ARE EQUALLY KNOWN AND UNDERSTOOD OVER A RANGE OF SPECIFIED PARAMETERS.

B03425

CATEGORIES OF CFD-RELATED EXPERIMENTATION

A. EXPERIMENTS DESIGNED TO UNDERSTAND FLOW PHYSICS

B. EXPERIMENTS DESIGNED TO DEVELOP PHYSICAL MODELS FOR CFD CODES

C. EXPERIMENTS DESIGNED TO CALIBRATE CFD CODES

D. EXPERIMENTS DESIGNED TO VALIDATE CFD CODES

ALL FOUR CATEGORIES ARE IMPORTANT AND ARE NECESSARY TO BUILD A MATURE CFD CAPABILITY

80 1424

AAC RECOMMENDATIONS FOR CFD VALIDATION

- NASA CLASSIFY ITS CFD-RELATED EXPERIMENTS INTO THE FOUR CATEGORIES DEFINED TO PROVIDE A FRAMEWORK FOR EVALUATION AND ALLOCATION OF RESOURCES
- NASA ADOPT A SHARPLY DEFINED PROGRAM PLAN FOR CFD VALIDATION
- NASA PAY CAREFUL ATTENTION TO INSTRUMENTATION AND FACILITIES REQUIRED TO PROVIDE DATA OF ADEQUATE ACCURACY AND IN THE FORM AND DETAIL REQUIRED FOR VALIDATION
- NASA ESTABLISH A COORDINATING BOARD FOR CFD VALIDATION RESPONSIBLE FOR DEFINING, COORDINATING, AND FOCUSING THE EFFORT. BOARD TO BE CHAIRED BY NASA HEADQUARTERS AND INCLUDE LEADERS FROM EACH OF THE RESEARCH CENTERS

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NEEDS AND STATUS OF CFD CODE VALIDATION

TERRY L. HOLST
THOMAS H. PULLIAM

NASA CFD Validation Workshop
NASA Ames Research Center
July 14-16, 1987

N92-70924

CURRENT AND FUTURE CFD RESEARCH AREAS

FLOW SEPARATION AND MIXING
INCOMPRESSIBLE FLOW
TRANSONIC FLOW (SHOCK/BL INTERACTION)
HIGH SPEED FLOWS (TRANSITIONAL, THERMAL AND CHEMICAL NONEQUILIBRIUM)
FLOWS INVOLVING COMBUSTION
UNSTEADY FLOWS (BUFFET, FLUTTER, ROTOR/STATOR, STORE SEPARATION)
HELICOPTER FLOWS (ACOUSTICS, BLADE/VORTEX INTERACTIONS)
VSTOL FLOWS (JET IN CROSS FLOW)
RAREFIED FLOWS
TWO-PHASE FLOW
NON-NEWTONIAN FLOW

➧ NEED VALIDATION FOR THESE AREAS

THE VALIDATION PROBLEM

AREAS REQUIRING VALIDATION	VALIDATION MECHANISM
• CFD PHYSICAL MODELS (GOVERNING EQUATIONS, BCs, GAS MODEL, TURBULENCE MODEL, VISCOSITY LAW)	COMPARISON WITH EXPERIMENT
• NUMERICAL ASPECTS (GRID EFFECTS, ARTIFICIAL DISSIPATION, DISCRETIZATION SCHEME)	CODE-TO-CODE COMPARISON (GRID REFINEMENT STUDIES, PARAMETER VARIATION, ETC.)
• CFD VALIDATION EXPERIMENTS	EXP-TO-EXP COMPARISONS
• CFD CODE USER EXPERTISE	TRAINING AND EXPERIENCE

MEASUREMENTS NEEDED FOR CFD CODE VALIDATION

MEASUREMENT*	DATA BASE**
FLOW FIELD SURVEYS	SMALL
SURFACE PRESSURE	LARGE
SKIN FRICTION	SMALL
HEAT TRANSFER	MEDIUM
W/T WALL MEASUREMENTS	SMALL
FLOW VISUALIZATION	MEDIUM
FREE STREAM CONDITIONS	LARGE
FORCE AND MOMENT	LARGE

---

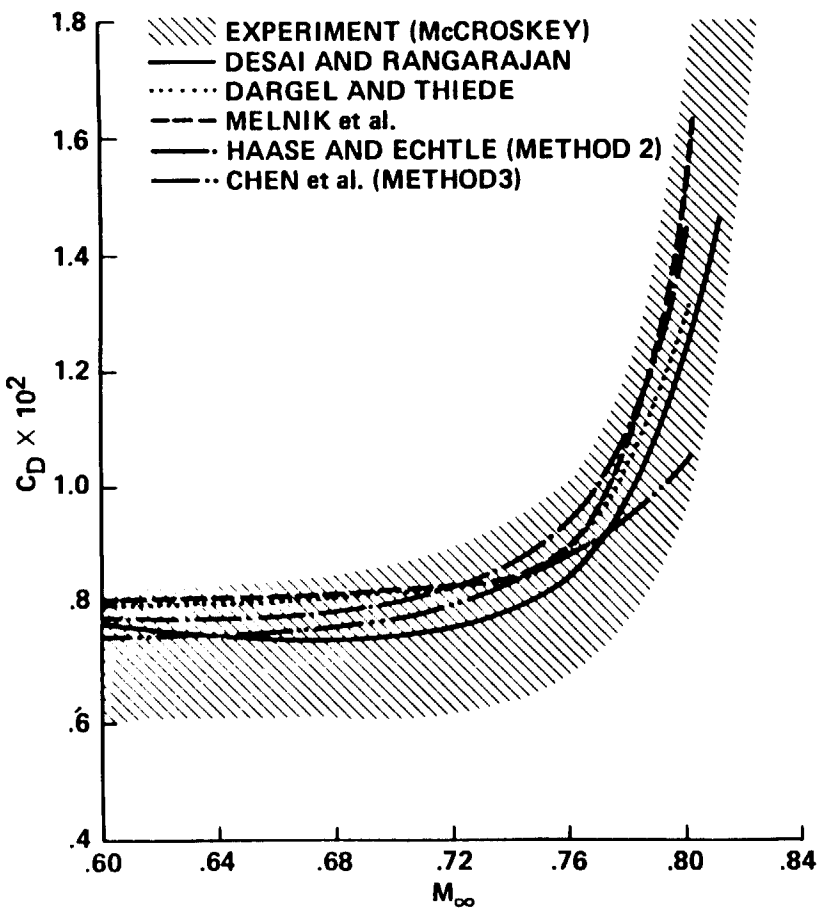
*UNSTEADY MEASUREMENTS ARE NEEDED IN MANY AREAS

**DATA BASE IS SMALL IN ALL AREAS FOR VERY HIGH SPEED FLOWS

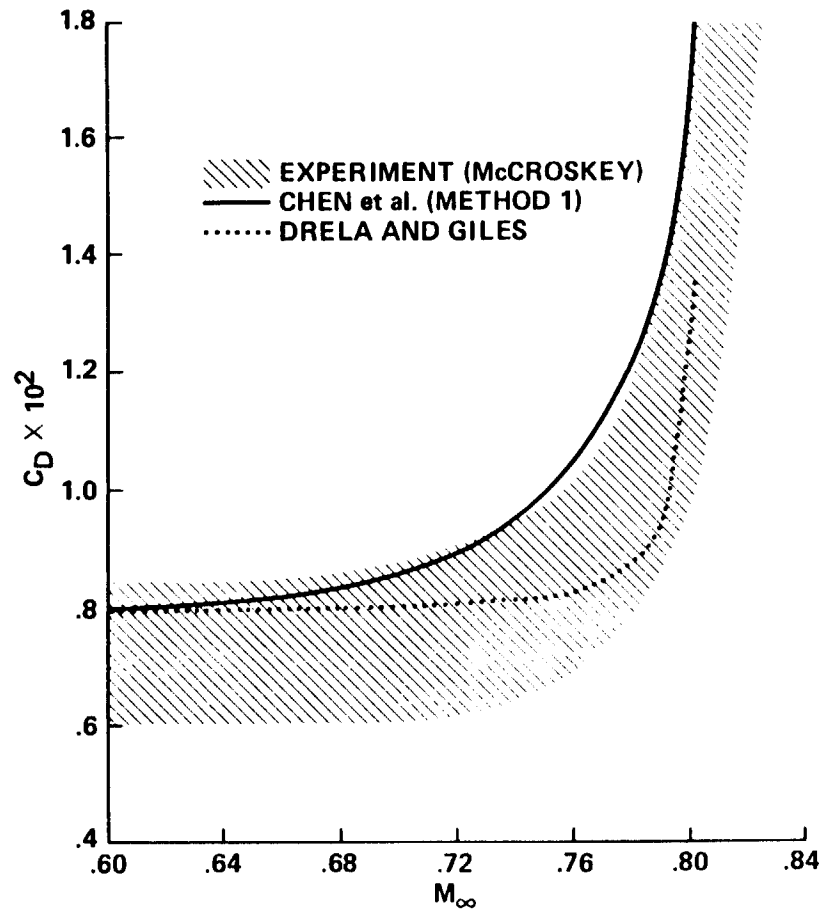
TRANSONIC DRAG-RISE COMPARISONS

NACA 0012 AIRFOIL, $\alpha = 0°$

FULL POTENTIAL + BOUNDARY LAYER RESULTS



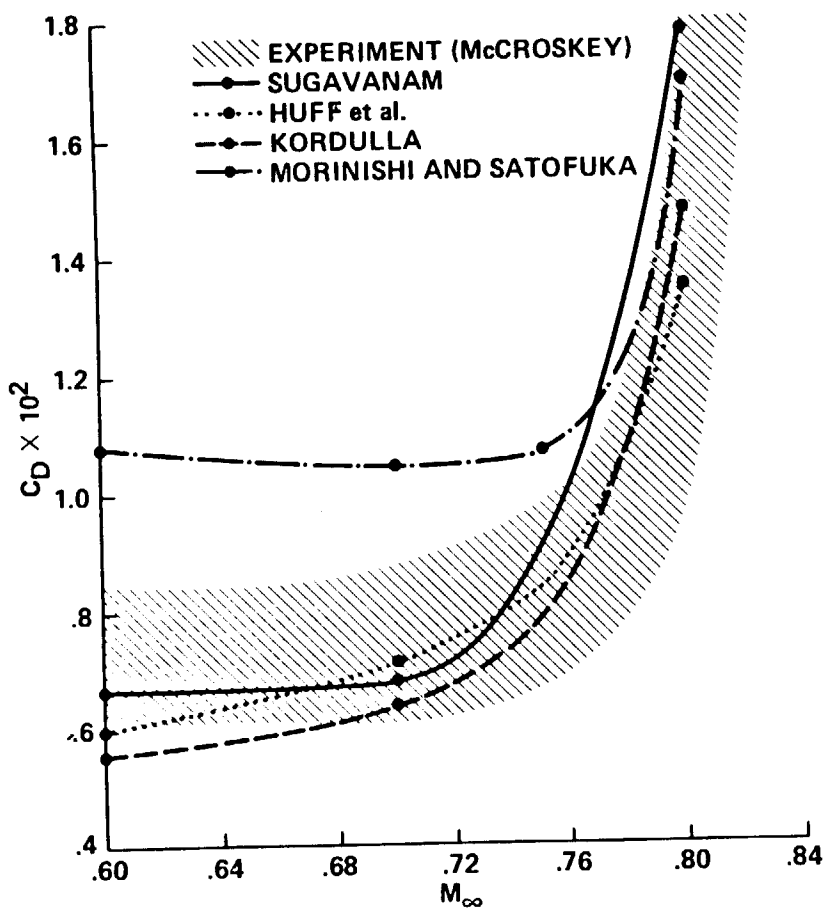
EULER + BOUNDARY LAYER RESULTS



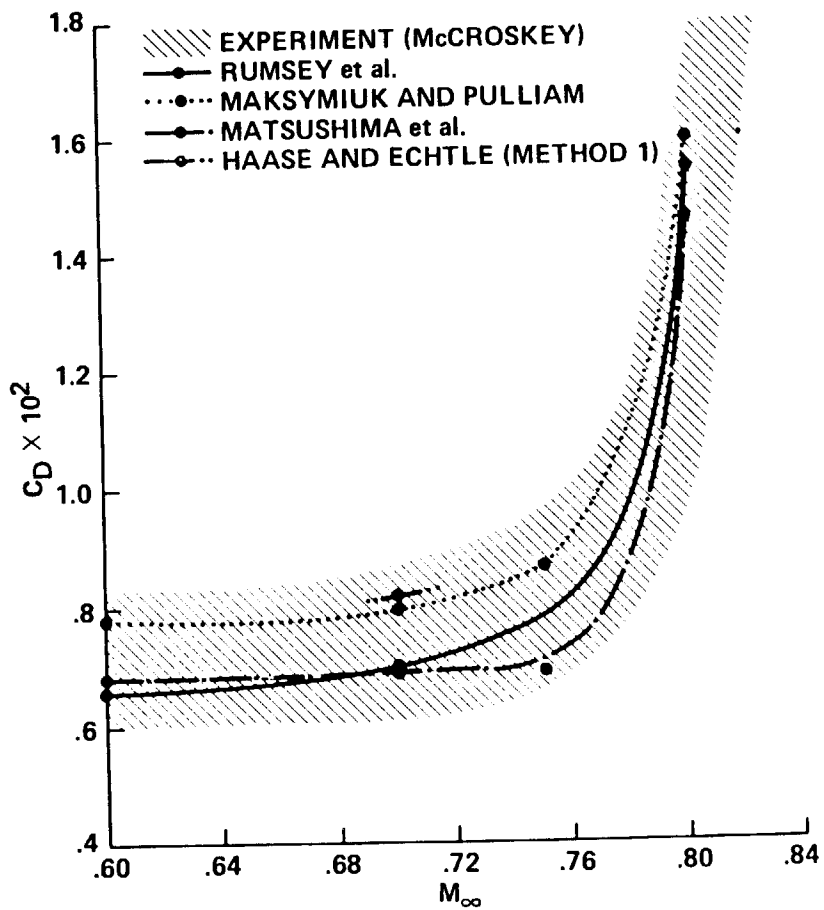
TRANSONIC DRAG-RISE COMPARISONS

NACA 0012 AIRFOIL, $\alpha = 0°$

COARSE-GRID NAVIER-STOKES RESULTS



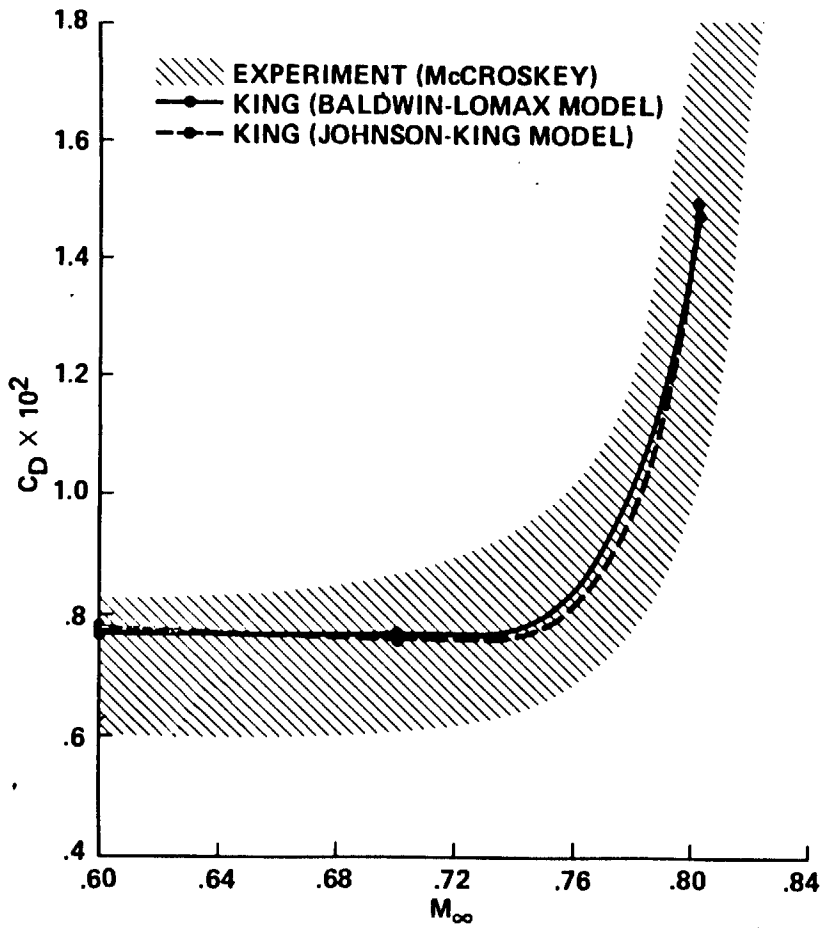
FINE-GRID NAVIER-STOKES RESULTS

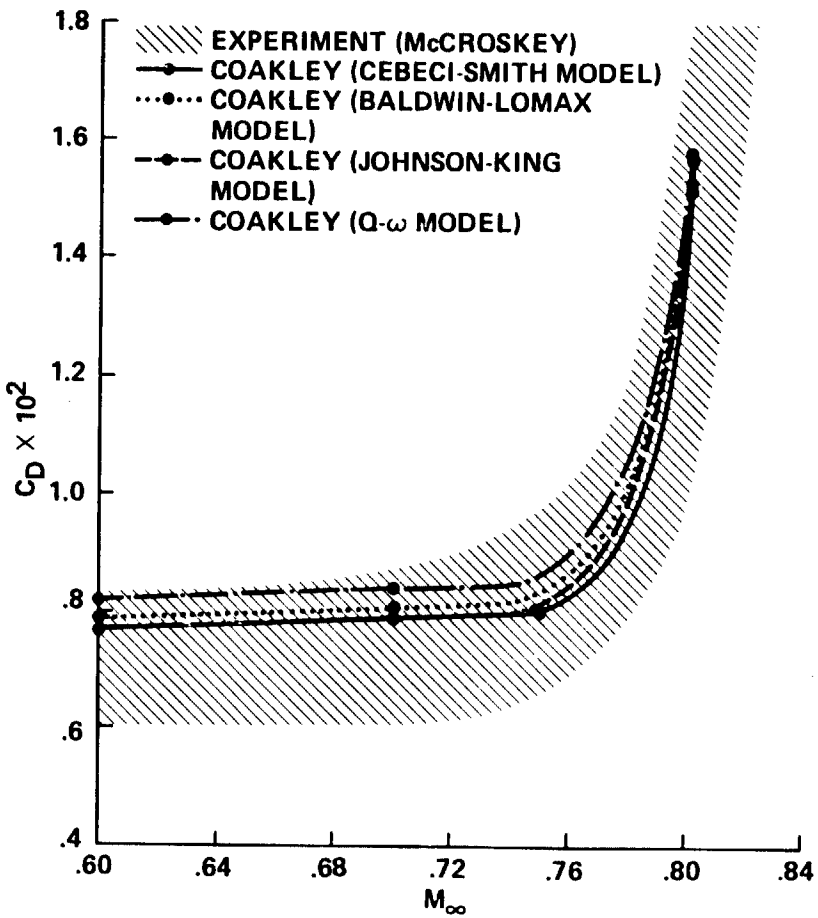


TRANSONIC DRAG-RISE COMPARISONS

NACA 0012 AIRFOIL, $\alpha = 0°$

TURBULENCE MODEL VARIATIONS (NAVIER-STOKES METHODS)





TNS CODE

OBJECTIVE:

TO DEVELOP A VISCOUS TRANSONIC CODE SUITABLE FOR SOLVING THE FLOW ABOUT REALISTIC AIRCRAFT CONFIGURATIONS

APPROACH:

- THIN-LAYERED NAVIER-STOKES EQUATIONS
- ZONAL GRID APPROACH
- BALDWIN-LOMAX TURBULENCE MODEL
- PULLIAM-CHAUSSEE DIAGONALIZED ITERATION SCHEME

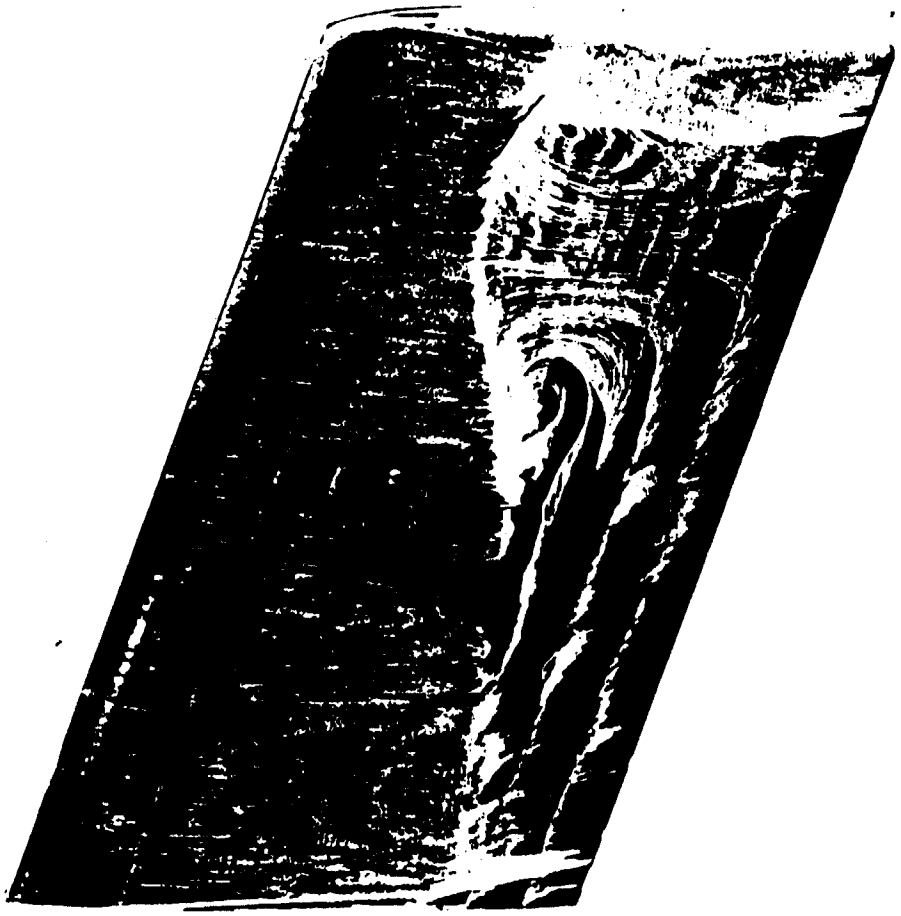
VALIDATION EXPERIMENTS:

- NACA 0012 WING (LOCKMAN-SEEGMILLER)
- WING C (KEENER, HINSON AND BURDGES)
- F-16A DATA (REUE, DOBERENZE, WILKINS)
- WING/FUSELAGE/STRAKE (OLSON)

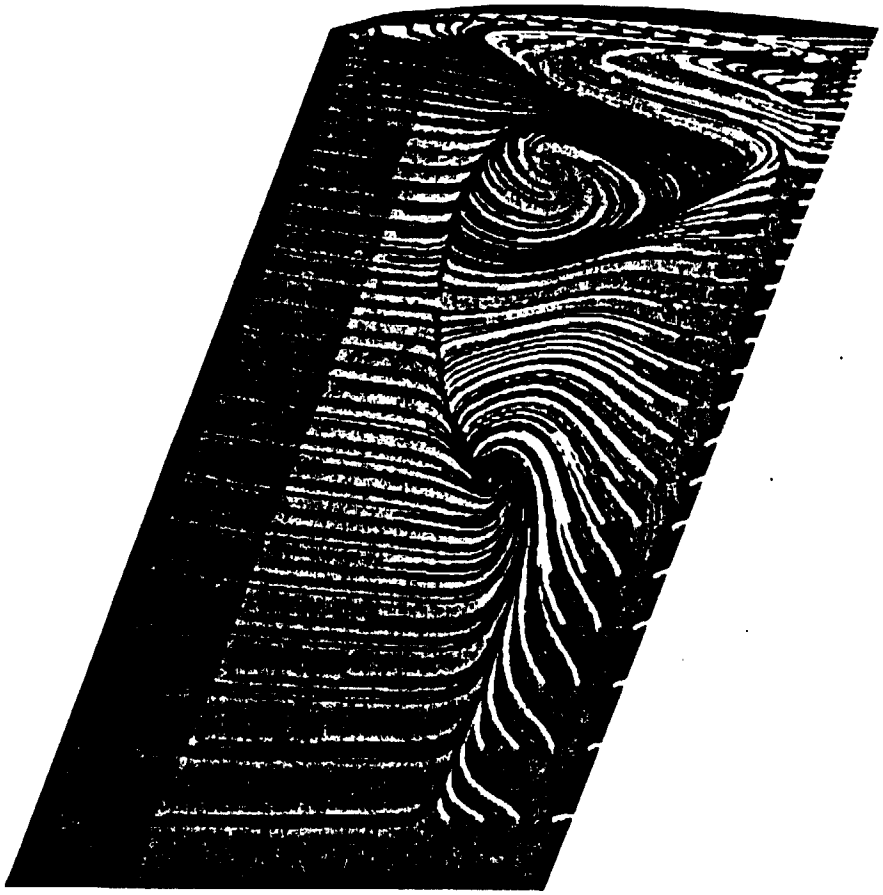
TRANSONIC MUSHROOM-TYPE SEPARATION

($M_\infty = 0.836$, $\alpha = 2°$, $Re_\infty = 8 \times 10^6$)

EXPERIMENT
(LOCKMAN AND SEEGMILLER)

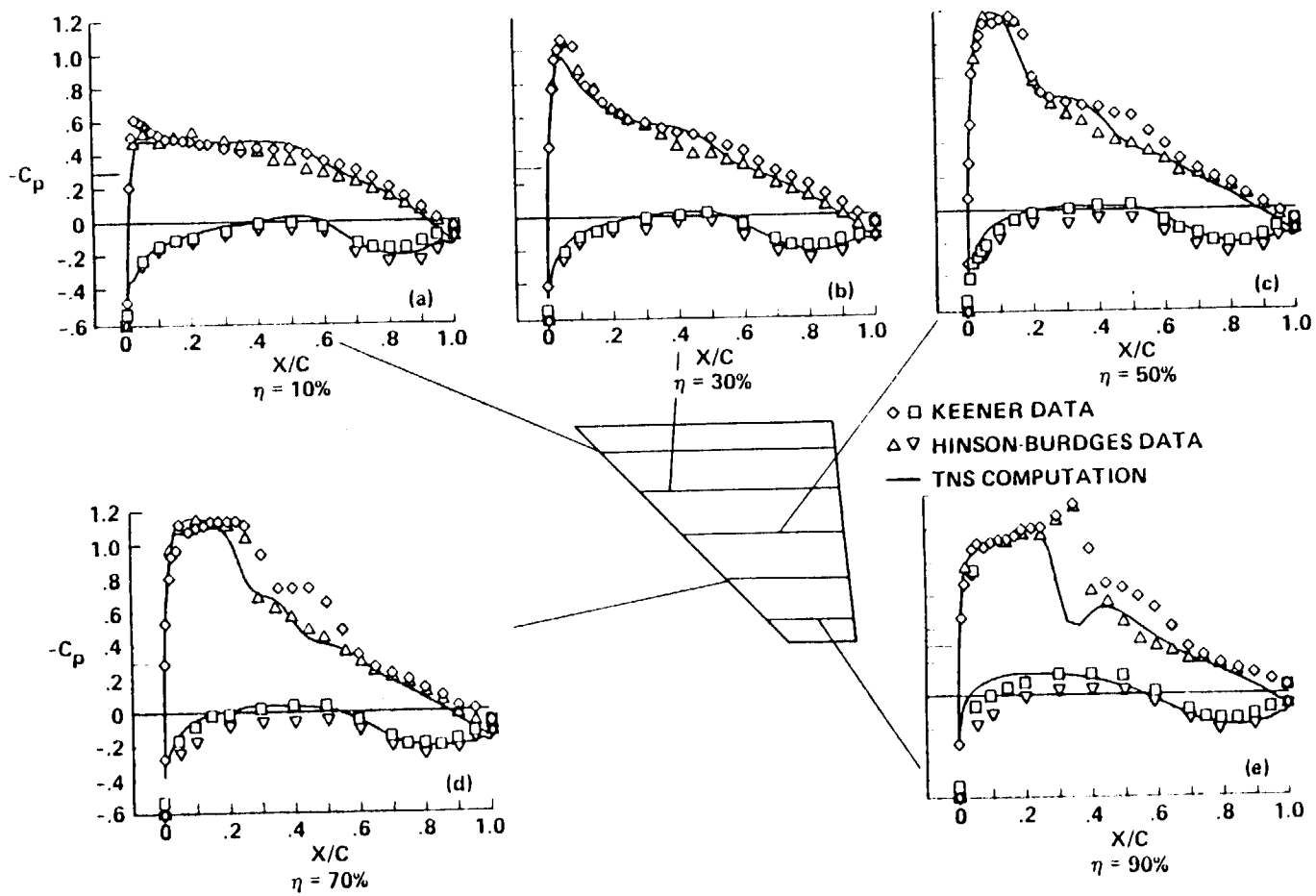


COMPUTATION
(KAYNAK AND FLORES)



PRESSURE COEFFICIENT COMPARISONS

WING C, $M_\infty = 0.85$, $\alpha = 5°$, $Re_\infty = 6.8 \times 10^6$



UPS CODE

OBJECTIVE:

DEVELOP A SPACE MARCHING FLOW SOLVER WITH IMPROVED SHOCK CAPTURING CHARACTERISTICS FOR THE EFFICIENT AND ACCURATE SIMULATION OF SUPERSONIC AND HYPERSONIC VISCOUS FLOW FIELDS

APPROACH:

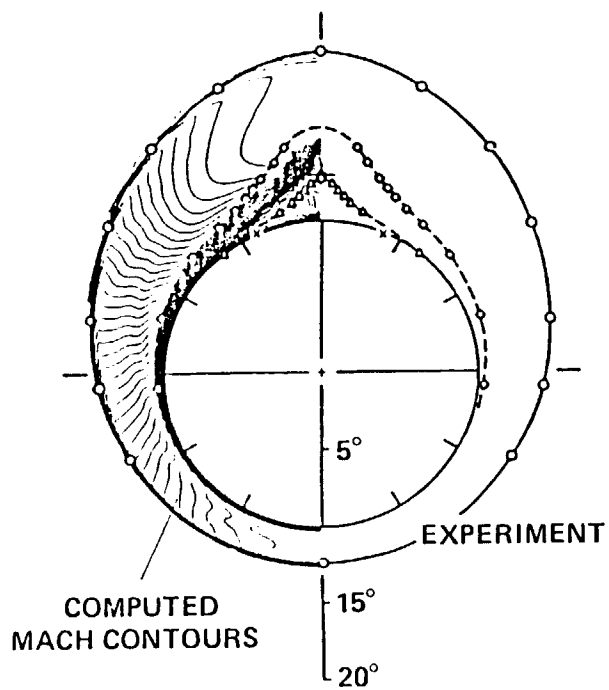
- PNS EQUATIONS (SPACE MARCHING)
- STREAMWISE FLUX SPLIT (VIGNERON)
- MODIFIED ROE'S SCHEME IN CROSSFLOW (2ND-ORDER FLUX-DIFFERENCE SPLITTING)
- IMPLICIT
- FINITE-VOLUME

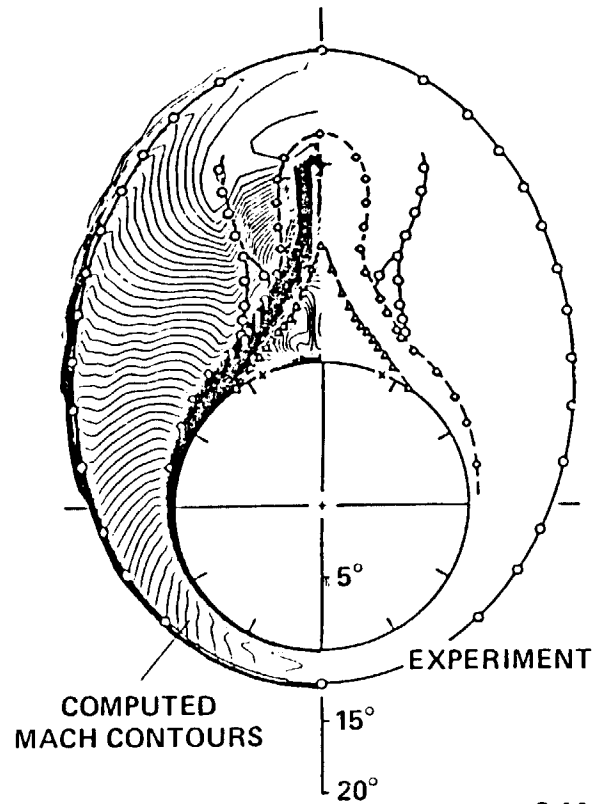
VALIDATION EXPERIMENTS:

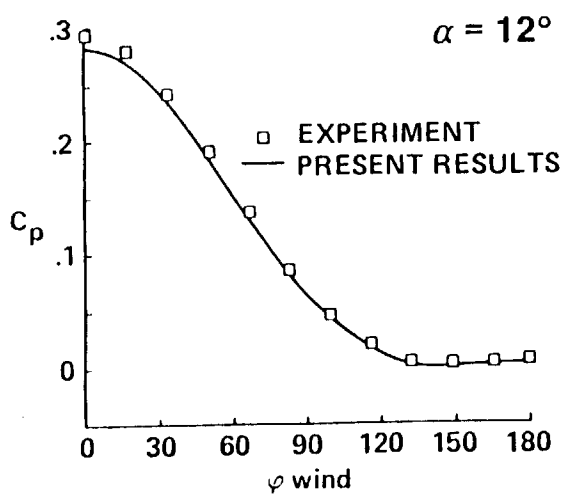
10° CONE; $M_\infty = 7.95$, $Re_L = 4 \times 10^5$ (TRACY)
14°/7° BI-CONE; $M_\infty = 10$, $Re_L = 1.0 \times 10^6$ (AEDC)
AMES ALL-BODY VEHICLE (LOCKMAN)

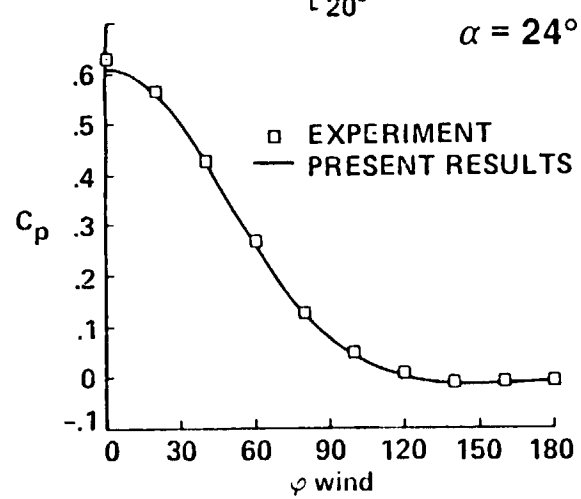
10° HALF-ANGLE CONE (LAMINAR)

$M_\infty = 7.95$, $Re_\infty = 4.101 \times 10^6/m$, $\tilde{x} = 0.1016$ m





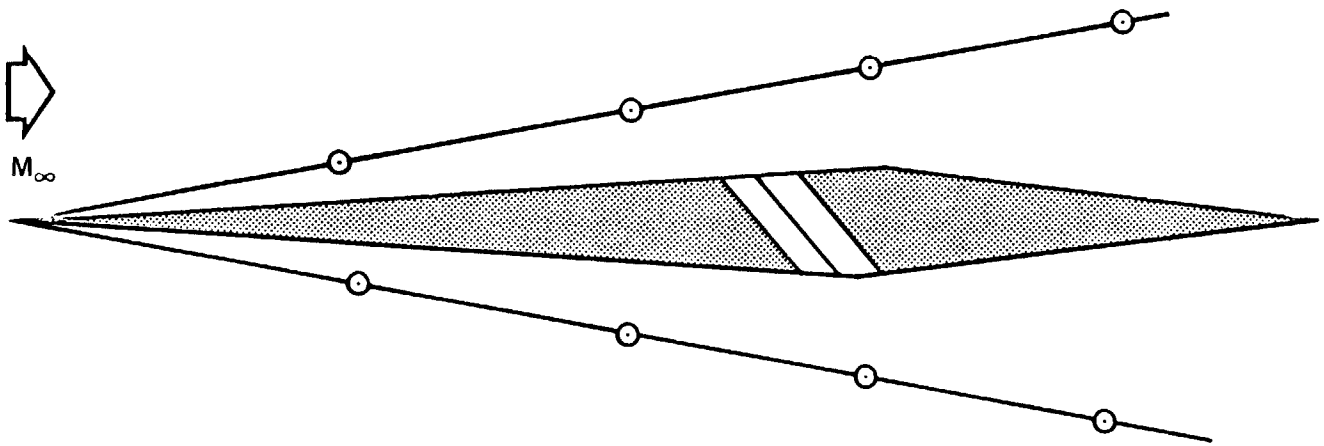




AMES ALL-BODY SHOCK SHAPES

$\alpha = 0°$, $M_\infty = 7.4$, $Re_L = 15 \times 10^6$

——— EXPERIMENT (LOCKMAN)
○ COMPUTATION (LAWRENCE)



CONCLUDING REMARKS

- MORE ATTENTION NEEDED ON CFD CODE VALIDATION
  - SOLUTION-TO-SOLUTION COMPARISONS TO EVALUATE NUMERICAL ERRORS
  - SOLUTION-TO-EXPERIMENTAL COMPARISONS TO EVALUATE PHYSICAL MODEL ERRORS
- MORE DETAILED EXPERIMENTS NEEDED TO:
  - HELP DEVELOP TURBULENCE MODELS
  - MORE COMPLETELY VALIDATE CFD CODES
  - EVALUATE DISAGREEMENTS WHEN THEY OCCUR
  - DETERMINE EXPERIMENTAL SCATTER

EXPERIMENTAL FLUID DYNAMICS

PART 1. BRIEF OVERVIEW

PART 2. FLOW MODELING AND VERIFICATION EXPERIMENTS – RFE

JOSEPH G. MARVIN
Chief, RFE Branch

PRESENTATION FOR
WORKSHOP ON CFD VALIDATION

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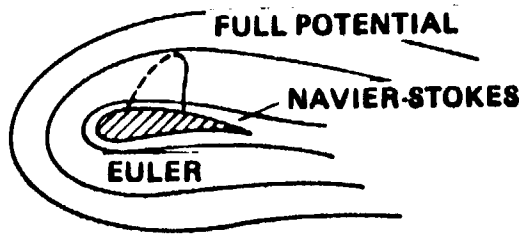
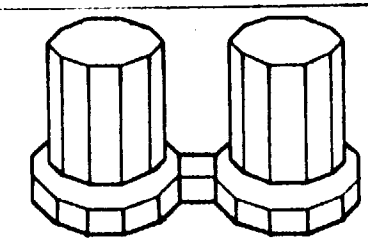
ITEMS PACING DEVELOPMENT OF CFD

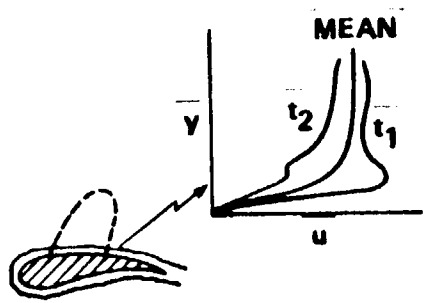
SOLUTION METHODOLOGY AND GRID GENERATION



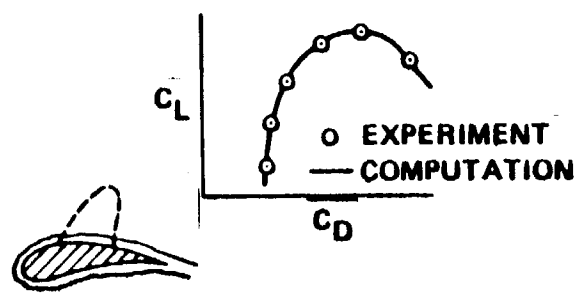
COMPUTER POWER



FLOW MODELING (TURBULENCE)

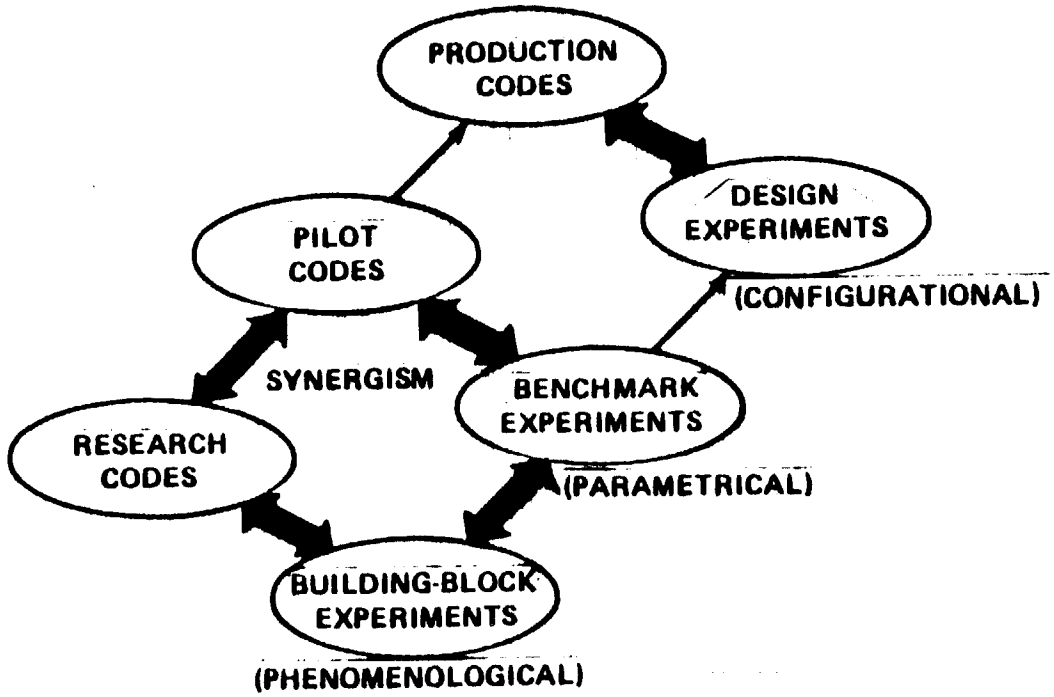


CODE VERIFICATION



MARVIN -

ROLE OF EXPERIMENT IN DEVELOPING CFD



MARVIN

EXPERIMENTAL REQUIREMENTS

EXPERIMENT	MEASUREMENTS (REPRESENTATIVE FOR TURBULENCE MODELING)	TEST CONDITIONS
BUILDING BLOCK (PHENOMENOLOGICAL)	SURFACE QUANTITIES FLOW FIELD QUANTITIES TURBULENCE INDIVIDUAL STRESSES CORRELATION LENGTHS STRUCTURE BOUNDARY CONDITIONS	REPRESENTATIVE FLIGHT M_∞, Re_∞
BENCHMARK (PARAMETRICAL)	SURFACE QUANTITIES FLOW FIELD QUANTITIES (SELECTED LOCATIONS) BOUNDARY CONDITIONS	VARY M_∞, Re, α OVER FLIGHT RANGES
DESIGN (CONFIGURATIONAL)	DRAG, LIFT, MOMENTS, HEAT LOADS, SHEAR LOADS BOUNDARY CONDITIONS	AS CLOSE TO FLIGHT M_∞, Re, α AS PRACTICAL

MARVIN

WIND TUNNEL REQUIREMENTS

BUILDING BLOCK AND BENCHMARK EXPERIMENTS

- APPROPRIATE SCALE AND SPEED RANGE
- VERSATILE, WITH WELL-DEFINED BOUNDARY CONDITIONS
- ACCESSIBILITY FOR NONINTRUSIVE INSTRUMENTATION
- COMPUTERIZED DATA SYSTEM
- DEDICATION TO VERIFICATION

MARVIN

CONCLUSIONS

EXPERIMENT PLAYS AN IMPORTANT ROLE IN DEVELOPING CFD

- FLOW MODELING OF COMPLEX PHYSICS
- VERIFICATION TO DETERMINE ACCURACY LIMITS (CONFIDENCE)

DIFFERENT TYPES OF EXPERIMENTS REQUIRE DIFFERENT TYPES OF DATA

- FLOW MODELING – PHENOMENOLOGICAL DATA FROM BUILDING BLOCK EXPERIMENTS
- VERIFICATION – PARAMETRICAL DATA FROM BENCHMARK EXPERIMENTS

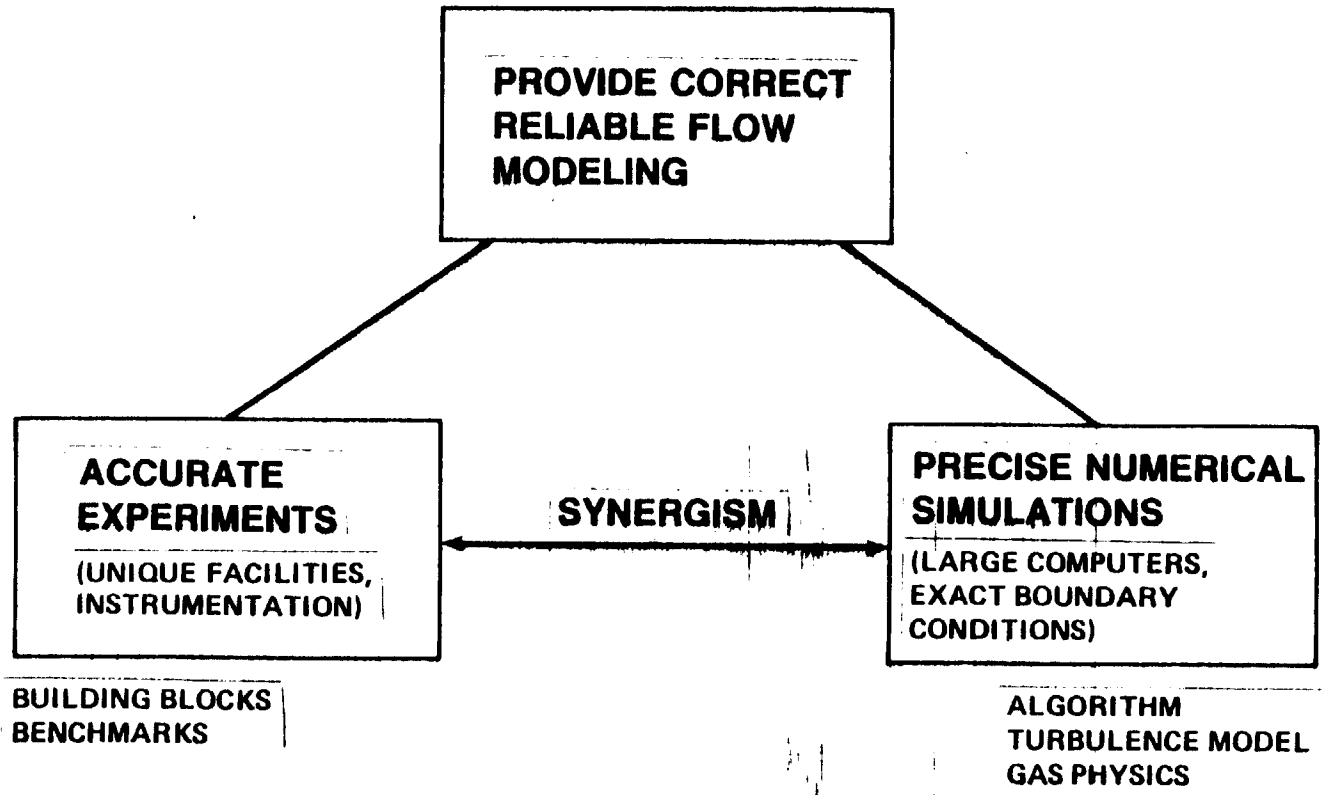
ELEMENTS OF FURTURE FLOW MODELING AND VERIFICATION EXPERIMENTS

- FOCUS ON IMPORTANT APPLICATIONS PACED BY FLOW MODELING
- INVOLVE CFD'ERS AND MODELERS IN PLANNING
- PROVIDE DATA ESSENTIAL TO MODELING AND VERIFICATION

MARVIN

EXPERIMENTAL FLUID DYNAMICS

TECHNOLOGY SUPPORTING CFD DEVELOPMENT OF R.A.N.S. CODES



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FLOW MODELING AND VERIFICATION
FY 1987
HQ'S APPROVED MODELING AND VERIFICATION PLAN

BENCHMARK EXPERIMENTS			BUILDING BLOCK EXPERIMENTS		
EXPERIMENT	TEAM	CODE(S)	EXPERIMENT	TEAM	ISSUE(S)
LOW ASPECT RATIO WING-BODY	FLORES OLSEN MATEER SEEGMILLER HAND	TNS	3-D SHOCK INTER-ACTION	HORSTMAN BROWN KUSSOY	TURBULENCE MODEL UNSTEADINESS
			3-D COMPRESSIBLE (PRESS. DRIVEN)	JOHNSON BROWN	TUBULENCE MODEL
SSME TAD	KWAK KAUL MONSON SEEGMILLER	INS 3-D	2-D TRANSONIC (CIRCON)	VIEGAS RUBESIN BROWN	TURBULENCE MODEL CURVATURE ENTRAINMENT
FIGHTER-LIKE VORTICAL FLOWS	HICKS SCHIFF ERICKSON	TNS FLO-26	3-SPIN FLOW (SHEAR DRIVEN W/ PRESS. GRAD.)	RUBESIN MOIN DRIVER	TURBULENCE MODEL
AIRFOIL W/WO PASSIVE SHOCK CONTROL	COAKLEY VAN DALSEM MATEER HAND SEEGMILLER	ARC 3-D TURF	3-D JUNCTION FLOW	JOHNSON EATON	TURBULENCE MODEL

FLOW MODELING AND VERIFICATION
FY 1987
UNSTEADY AND FLOW PHYSICS EXPERIMENTS

BENCHMARK EXPERIMENTS			BUILDING BLOCK EXPERIMENTS		
EXPERIMENT	TEAM	CODE(S)	EXPERIMENT	TEAM	ISSUE(S)
ROTORCRAFT RELATED	CARADONNA	UN-STEADY N.S. AND OTHER	TURBULENT SHEAR LAYERS	MANSOUR MEHTA KING	CONTROL OF 3-D EFFECTS
			TURBULENT BOUNDARY LAYERS	SPALART WESTPHAL	SIMULATION OF INCIPIENT SEPARATION
			3-D SEPARATED FLOWS	SCHIFF ZILLIAC TOBAK	TOPOLOGY ASYMMETRY BOUNDARY CONDITIONS
			UNSTEADY VISCOUS FLOWS	DAVIS McLACHLAN LONG	3-D SEPARATION
			STEP FLOW	KIM MOIN ROBINSON	FLOW DYMANICS L.E.S. AND S.

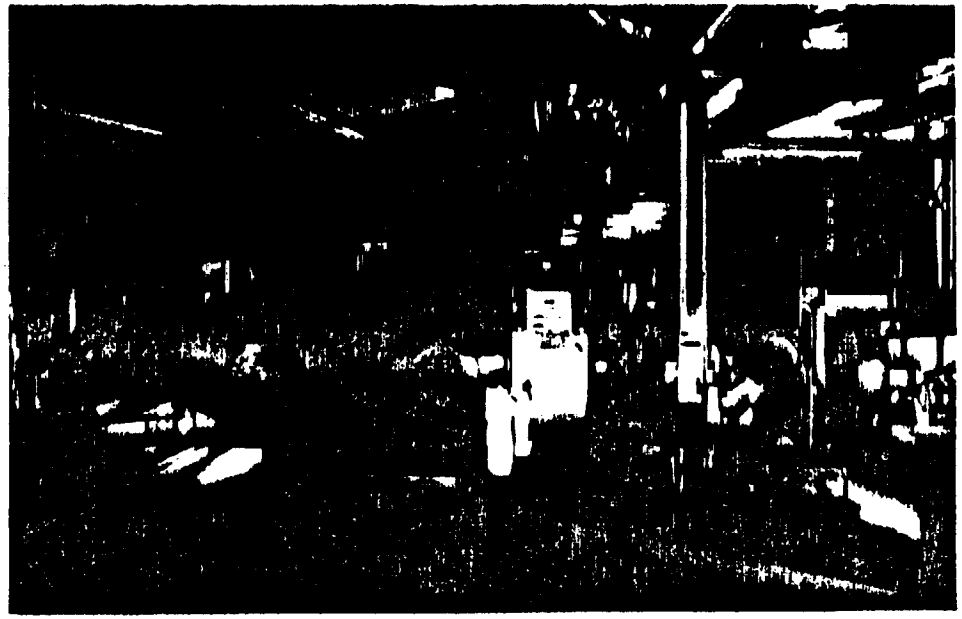
FLOW MODELING AND VERIFICATION
FY 1987
NASP

BENCHMARK EXPERIMENTS			BUILDING BLOCK EXPERIMENTS		
EXPERIMENT	TEAM	CODE(S)	EXPERIMENT	TEAM	ISSUE(S)
GENERIC HYPERSONIC ALL BODY	LAWRENCE LOCKMAN	PNS	HYPERSONIC SHOCK INTERACTION	HORSTMAN KUSSOY	TURBULENCE MODEL COMPRESSIBILITY
EXHAUST NOZZLE	CHAPMAN LOCKMAN FEIEREISEN	3-D RANS	SLENDER CONE/ DRAG/SHOCK STRUCTURE	CHAPMAN KRUSE CHAUSSEE	REAL GAS EFFECTS

AN EXAMPLE OF A VERSATILE WIND TUNNEL

AMES HIGH REYNOLDS CHANNEL

TUNNEL 2



MARVIN

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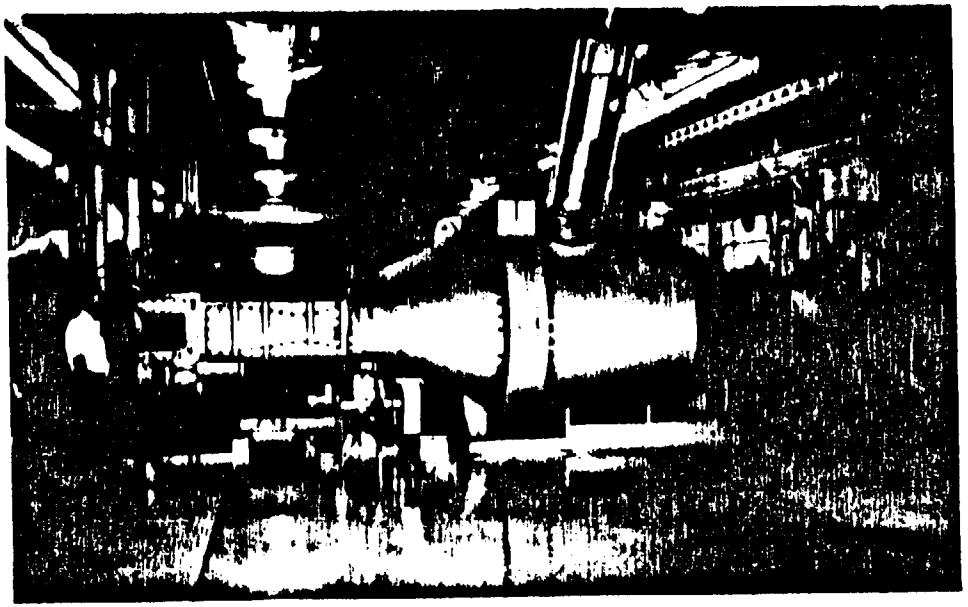
AN EXAMPLE OF A VERSATILE WIND TUNNEL

AMES HIGH REYNOLDS CHANNEL

TUNNEL 1



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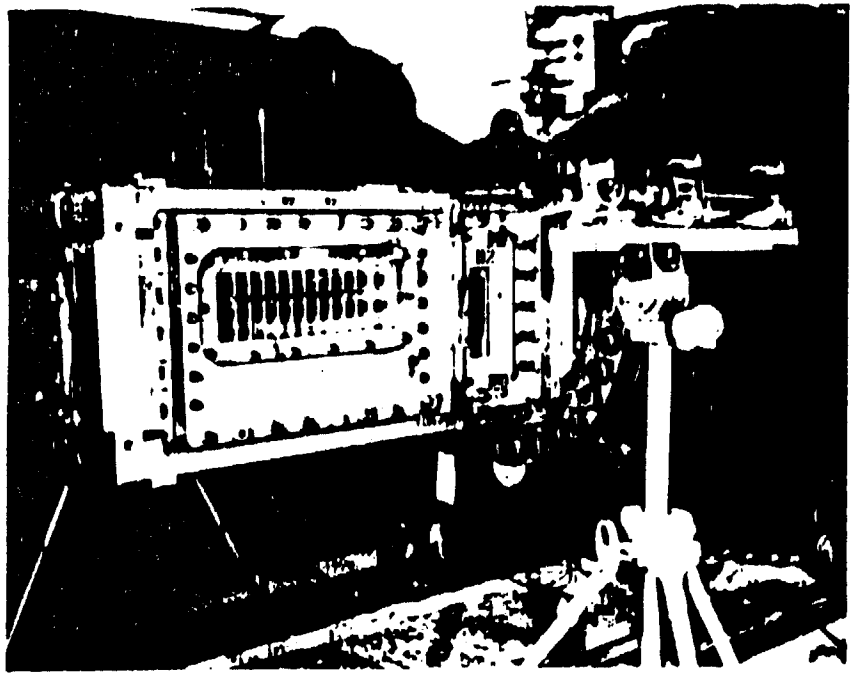
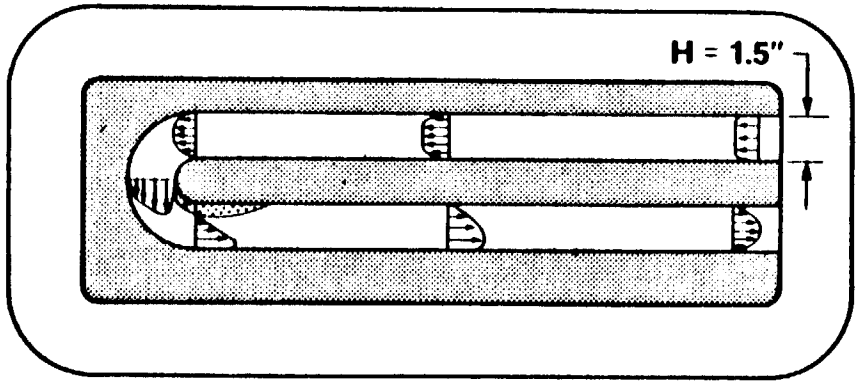
SSME TURN-AROUND DUCT EXPERIMENT
NASA AMES HIGH REYNOLDS CHANNEL I

VIEW SHOWING LASER SKIN-FRICTION INTERFEROMETER



FLOW FIELD AND GEOMETRY



MEASUREMENTS

$RE_H = 0.1 - 3.0 \times 10^6$

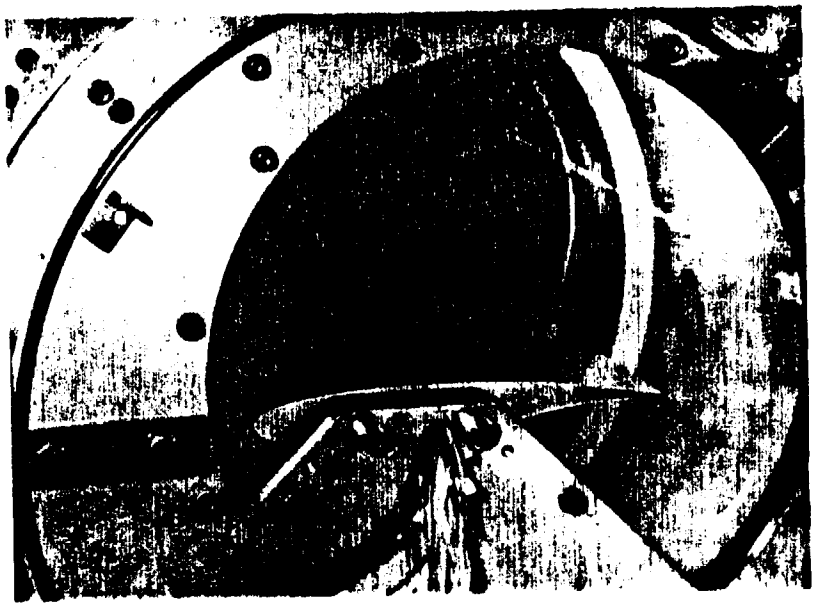
$M = 0.1 - 0.3$

SURFACE: p_w, c_f, OIL FLOW

FLOW FIELD: U, V, $\overline{u'}$, $\overline{v'}$, $\overline{u'v'}$

VERIFICATION EXPERIMENT FOR TRANSONIC FLOW CODES

SUPERCRITICAL AIRFOIL WITH LDV



TEST CONDITIONS

$0.73 \leq M \leq 0.80$

$2 \times 10^6 \leq Re \leq 6 \times 10^6$

$0.5 \leq \alpha \leq 1.5$

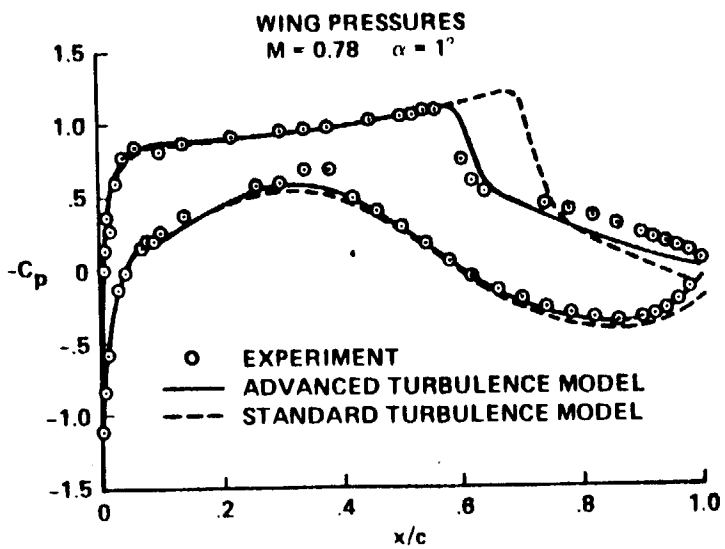
MEASUREMENTS

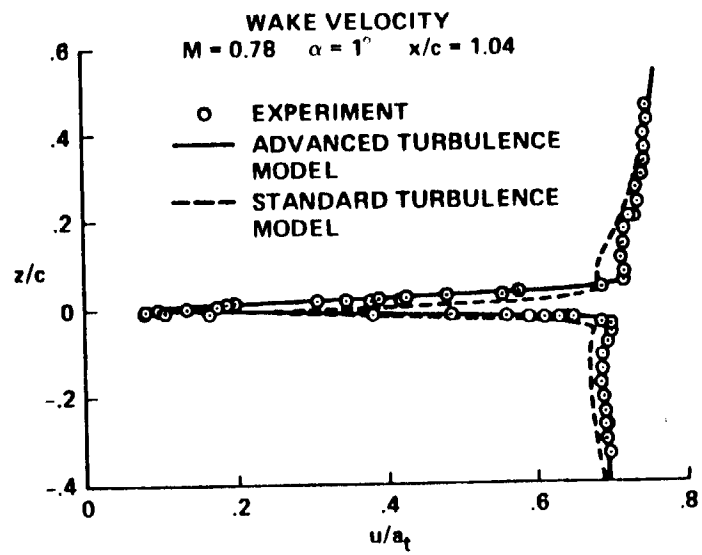
PRESSURE ($\bar{p}$, $\langle P' \rangle$)

FLOW FIELD (U, V, $\overline{u'v'}$ . . .)

OIL FLOW

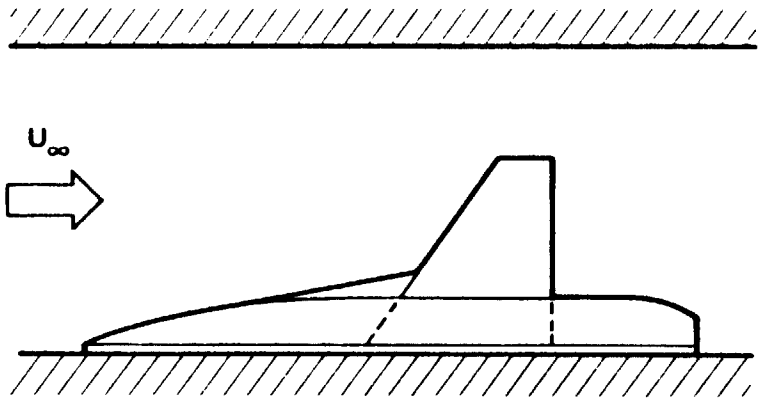
LIFT, DRAG





LOW ASPECT-RATIO WING/BODY EXPERIMENT

DATA BASE FOR TNS CODE



CHANNEL:

- TAPERED TOP AND BOTTOM SOLID WALLS FOR B.L. GROWTH (NO CONTOURING)

MODEL

- OGIVE-CYLINDER HALF-BODY
- WING
  - NACA 64A008 STREAMWISE SECTION
  - ASPECT RATIO = 3.2 (2.8, EXPOSED)
  - TAPER RATIO = 0.25
  - L.E. SWEEP ANGLE = 36.9°
- STRAKE – ROUNDED LEADING EDGE

TEST CONDITIONS

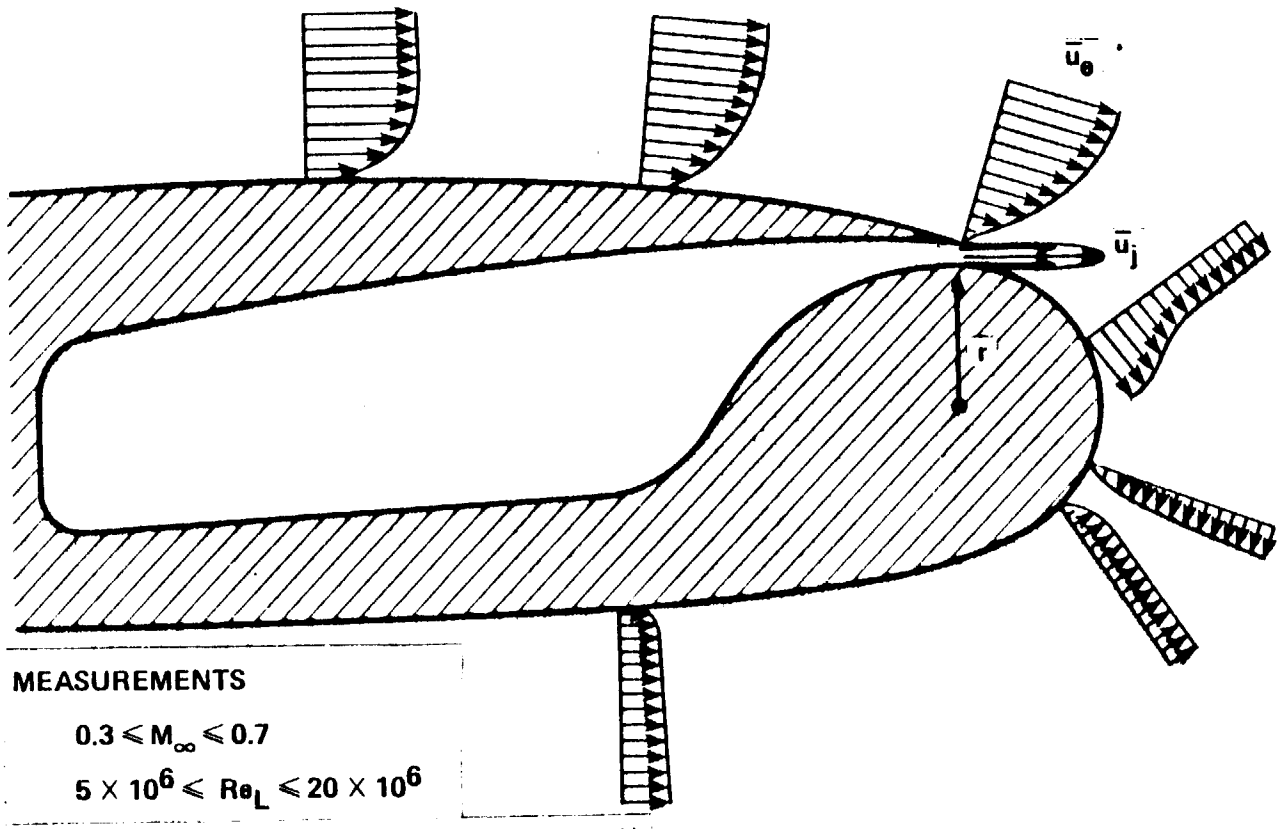
- M_∞ = 0.5 TO 0.8
- $Re_{\infty,\bar{c}} = 1 \times 10^6$ TO 10×10^6
- $\alpha = 0°$ TO 15°

MEASUREMENTS (INDIVIDUAL COMPONENTS/ COMPLETE MODEL)

- FLOW VISUALIZATION
  - SURFACE – OIL FLOW
  - FLOW FIELD – VAPOR SCREEN
- SURFACE PRESSURES (WING, WALLS)
- MEAN VELOCITY SURVEYS (2 COMPONENT LDV) (WING ALONE)
- FLOW FIELD PRESSURE PROBES (MULTI-ORIFICE)

TURBULENCE MODELING EXPERIMENT — CIRCULATION CONTROL AIRFOIL

TRAILING-EDGE GEOMETRY



MEASUREMENTS

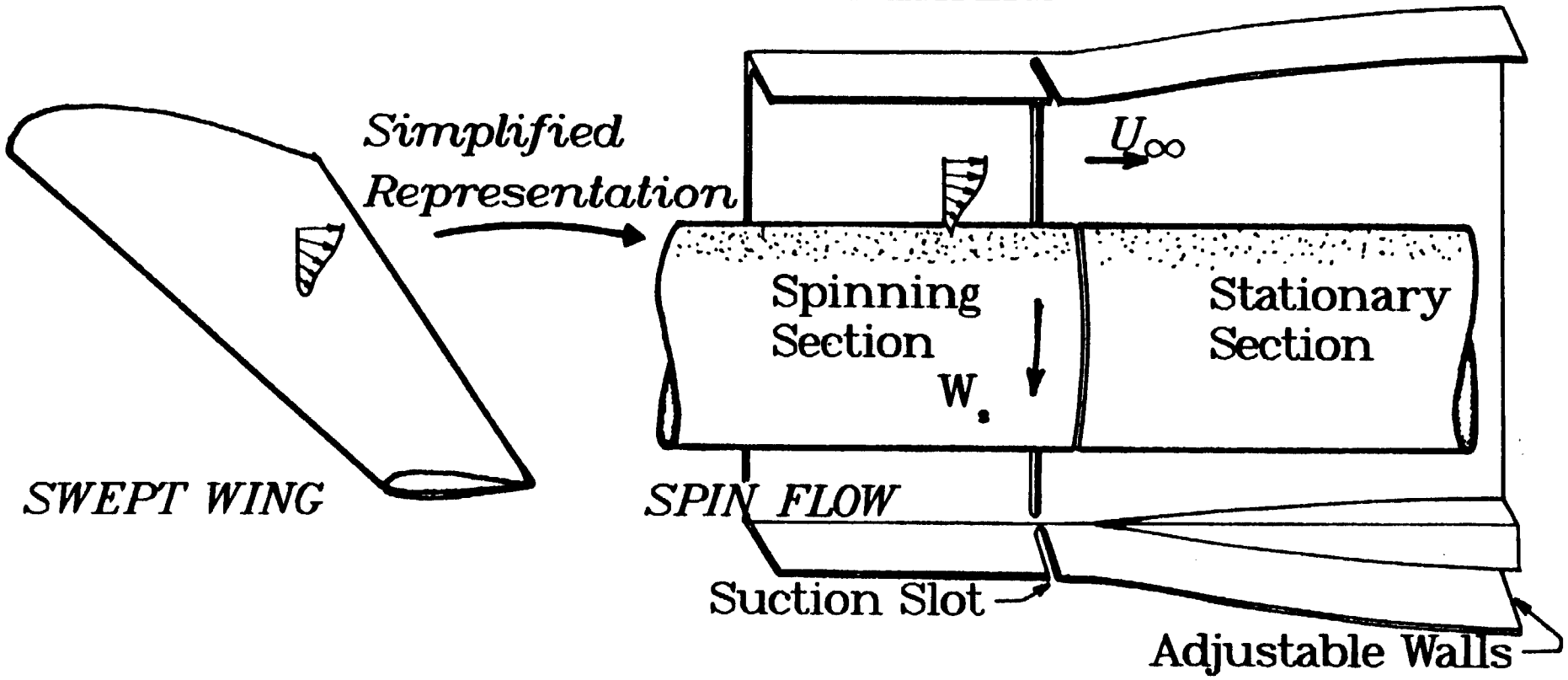
$0.3 \leqslant M_\infty \leqslant 0.7$

$5 \times 10^6 \leqslant Re_L \leqslant 20 \times 10^6$

SURFACE: p_w (MODEL AND TUNNEL WALLS), c_f, OIL FLOW

FLOW FIELD: p_t, u, v, REYNOLDS STRESSES

SPIN FLOW EXPERIMENT FOR STUDY OF 3–D BOUNDARY LAYERS



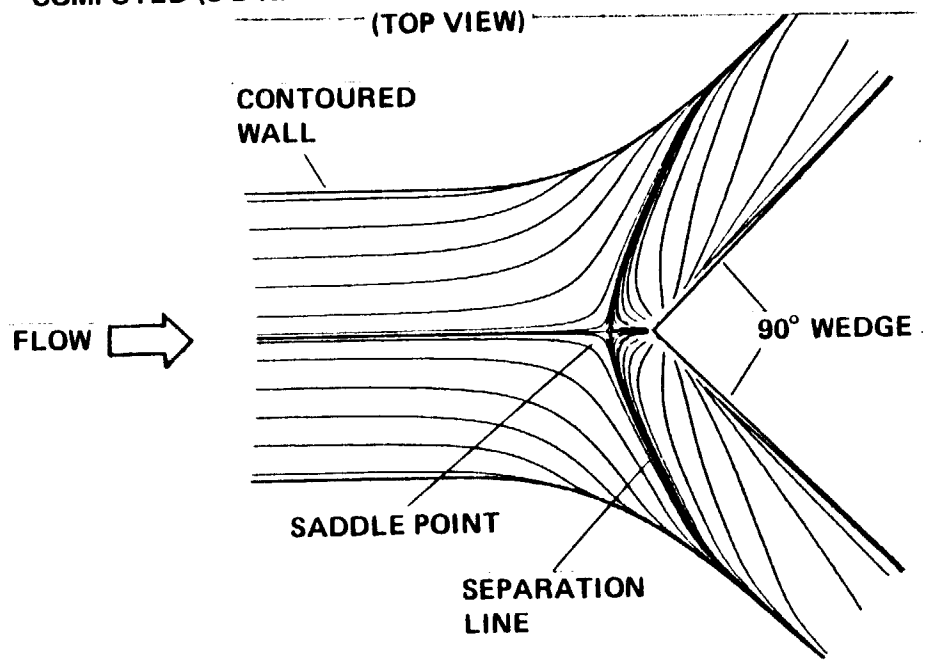
IDEALIZED BUILDING BLOCK EXPERIMENT

- Simplified axisymmetric geometry that contains the features of a 3–D turbulent boundary layer.
- 0.3m x 0.3m test section, $Re_\Theta = 6000$, $U_\infty = 35$ m/s, $W_s = 35$ m/s
- Measurements: C_p, C_f, U,V,W and all Reynolds Stresses

3-D JUNCTION FLOW

LOW-SPEED SHARP WEDGE FLOW WITH SEPARATION

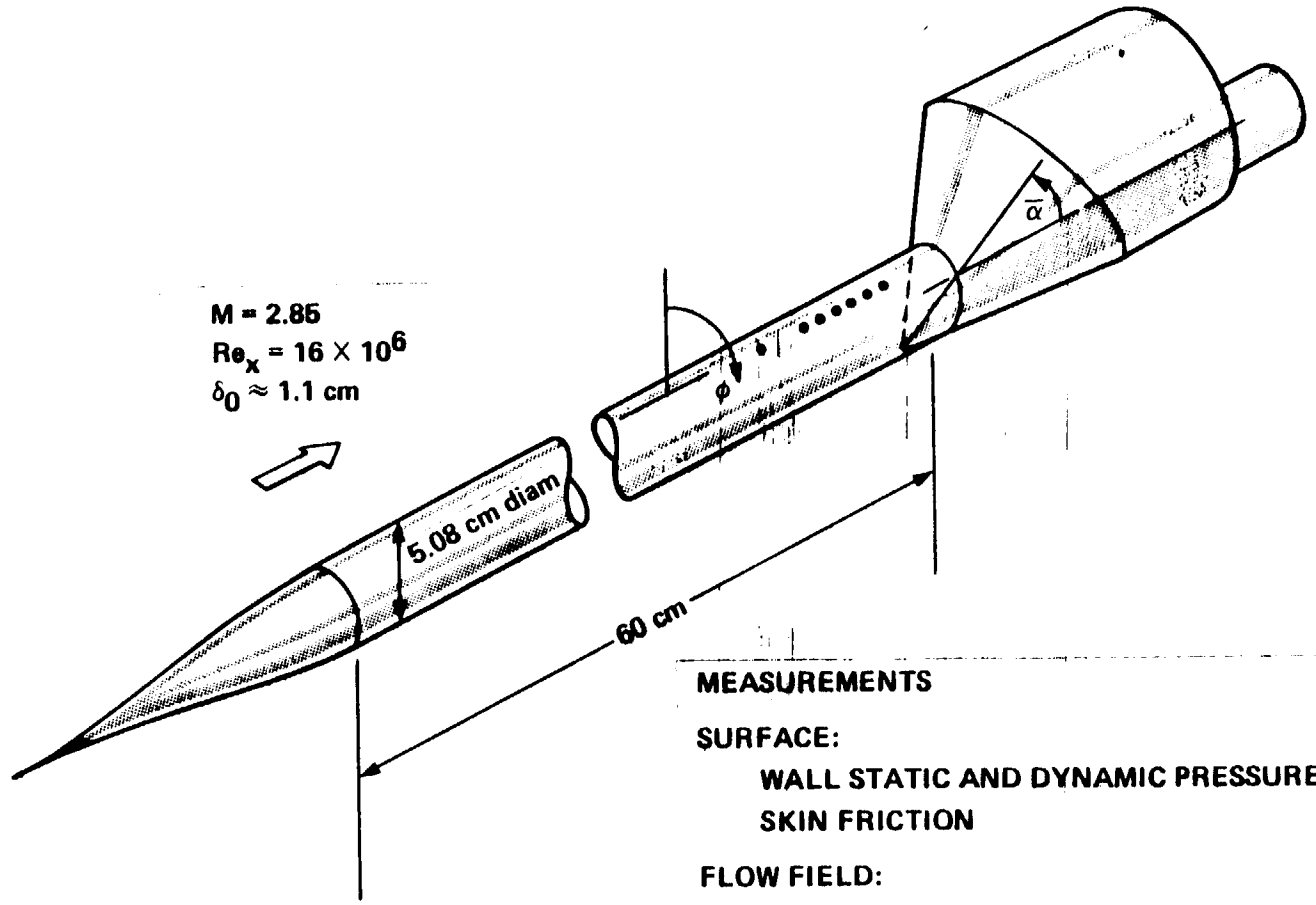
COMPUTED (3-D NAVIER-STOKES) SURFACE FLOW PATTERN
(TOP VIEW)



TURBULENT BOUNDARY LAYER SEPARATION AMENABLE TO EXPERIMENT AND TO 3-D NAVIER-STOKES CALCULATIONS

- SIMPLE GEOMETRY
- WELL DEFINED B.C.'s
- MEASUREMENTS OF C_p, c_f, u, v, w AND REYNOLDS STRESSES

TURBULENCE MODELING EXPERIMENT — SUPERSONIC SHOCK-WAVE BOUNDARY-LAYER INTERACTION



MEASUREMENTS

SURFACE:

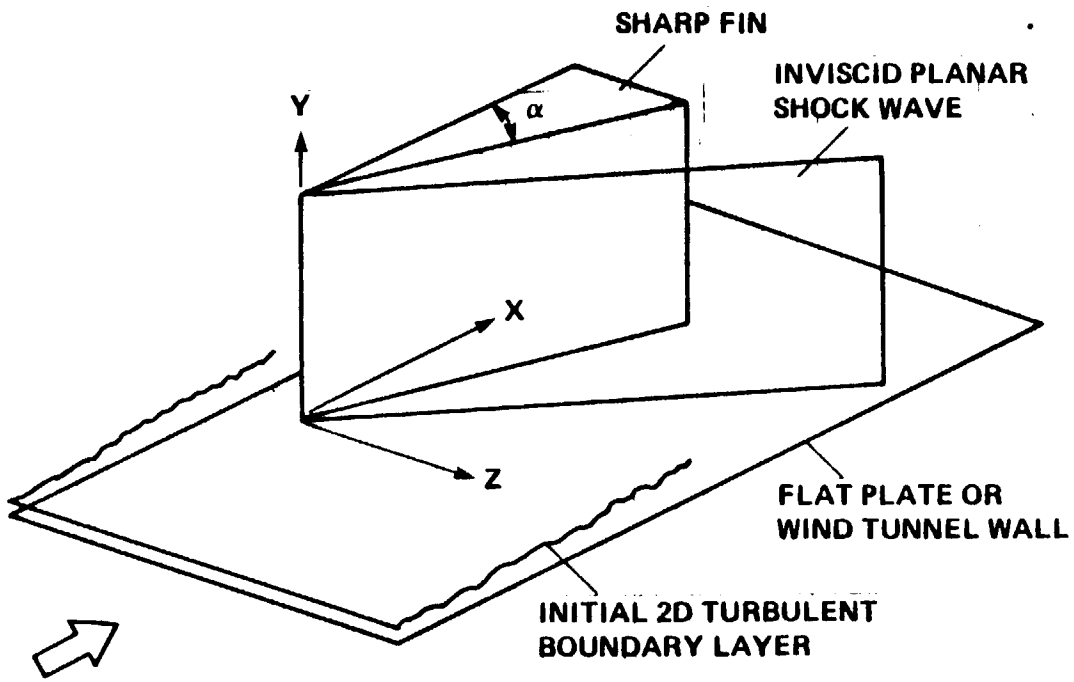
- WALL STATIC AND DYNAMIC PRESSURES
- SKIN FRICTION

FLOW FIELD:

- ρ, u, v, w, REYNOLDS STRESSES

3-D SHOCK INTERACTION EXPERIMENT

FLOW GEOMETRY



LOCATION OF EXPERIMENT: PENN STATE

$M_\infty \approx 2.4 - 4$

$\alpha = 4 - 22°$

$Re_x \approx 10 \times 10^6$

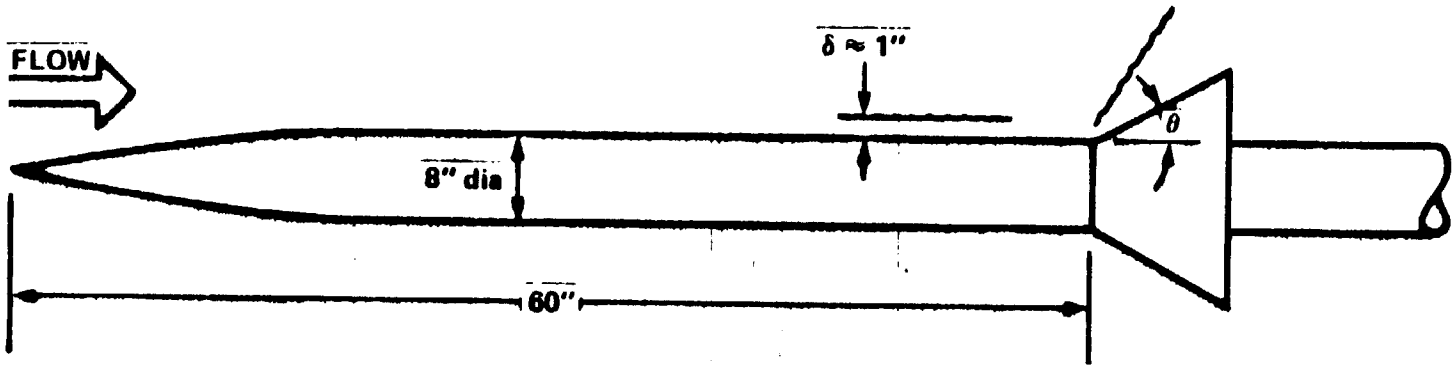
MEASUREMENTS

SURFACE: OIL FLOW, p_w, c_f

FLOW FIELD: VAPOR SCREEN, p_{t_2}, YAW ANGLE

HYPERSONIC SW/BL INTERACTIONS

PHASE I



RANGE OF PARAMETERS

- M_∞: 5 → 14
- Re_∞/ft: $0.25 \times 10^6 \rightarrow 7.4 \times 10^6$
- θ: 20° → 50°

- LAMINAR → TURBULENT
- UNSEPARATED → SEPARATED
- STEADY → UNSTEADY
- 2D ONLY

MEASUREMENTS

- SURFACE: p_w, p'_w, $\dot{q}_w$, SKIN FRICTION LINES
- FLOW FIELD: p, P, T, vs. y, U, V, u', v', $\overline{u'v'}$, TKE, SHADOWGRAPHS

ANTICIPATED PROBLEMS

- LDV FEASIBILITY: SEEDING/OPTICS/ELECTRONICS/ACCURACY

ACCURACY OF DATA

- ≈ 5% ERROR IN MEAN QUANTITIES
- UNKNOWN ERROR IN TURBULENT QUANTITIES

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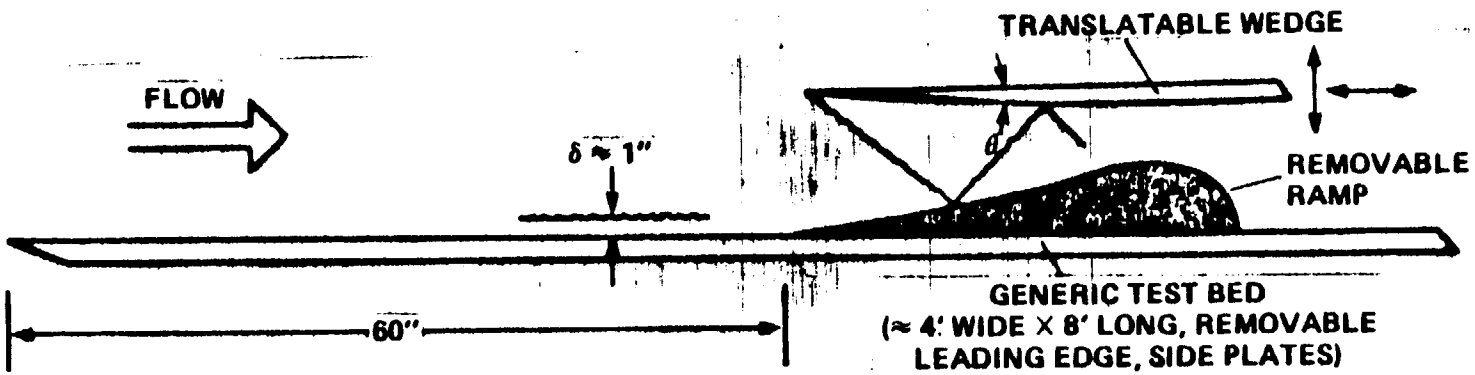
HYPERSONIC SW/BL INTERACTIONS

PHASE II



RANGE OF PARAMETERS

- M_∞: 5 → 14
- Re_∞/ft: $0.25 \times 10^6 \rightarrow 7.4 \times 10^6$
- θ: 5° → 50°

- LAMINAR → TURBULENT
- STEADY → UNSTEADY (?)
- 2D (?) → 3D

MEASUREMENTS

- SURFACE: p_w, p'_w, $\dot{q}_w$, SKIN FRICTION LINES
- FLOW FIELD: p, P, T, vs. y, PITCH, YAW, U, V, u', v', $\overline{u'v'}$, TKE, SHADOWGRAPHS

ANTICIPATED PROBLEMS

- LDV FEASIBILITY (IN GENERAL)
- LDV FEASIBILITY (THROUGH QUARTZ SIDE PLATES ON INLET)
- SHADOWGRAPH FEASIBILITY (THROUGH QUARTZ SIDE PLATES ON INLET)

ACCURACY OF DATA

- ≈ 5% ERROR IN MEAN QUANTITIES
- UNKNOWN ERROR IN TURBULENT QUANTITIES

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FIRST NASA WORKSHOP ON
CFD VALIDATION

JULY 14-16, 1987

FLOW PHYSICS

SANFORD DAVIS

N92-70926

FLOW PHYSICS VALIDATION
CONCLUSIONS

- THE COUPLING OF COMPUTATIONAL ANALYSIS AND EXPERIMENT IS CRITICAL IN DEVELOPING NEW AERODYNAMIC INSIGHTS
- NEW METHODS FOR ANALYZING/INTERPRETING DATA NEED TO BE DEVELOPED IN SMALL-SCALE RESEARCH STUDIES AND MIGRATED TO LARGE-SCALE TECHNOLOGY PROGRAMS

FIGHTER-LIKE VORTICAL FLOW EXPERIMENTS/COMPUTATIONS

Presented at

NASA CFD VALIDATION WORKSHOP

July 14-16, 1987

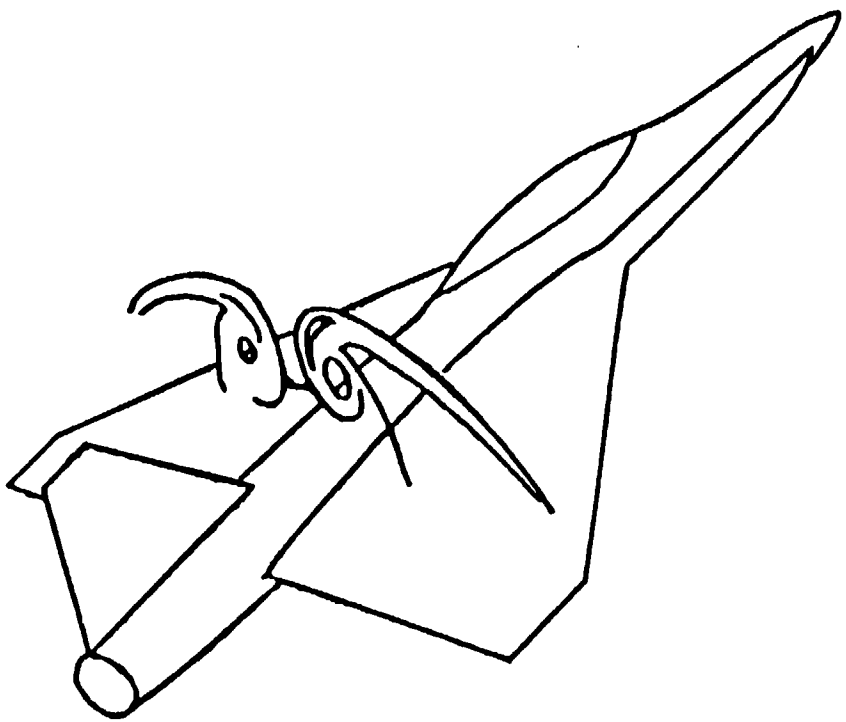
Larry L. Erickson
415-694-5881

NASA AMES
Aerodynamics Division

N92-70927

OBJECTIVE

- DETERMINE ABILITY OF EULER & NAVIER-STOKES CODES TO PREDICT VORTEX/SHOCK-DOMINATED FLOWS REPRESENTATIVE OF MODERN FIGHTERS



MOTIVATION

- FIGHTERS ARE, WILL BE, OPERATING BEYOND $C_{L_{MAX}}$
- HIGH – α VORTEX/SHOCK-DOMINATED FLOWS ARE NOT WELL UNDERSTOOD
- CURRENT DESIGN IS BY TRIAL-AND-ERROR
- DATA BASE INADEQUATE FOR CFD VALIDATION

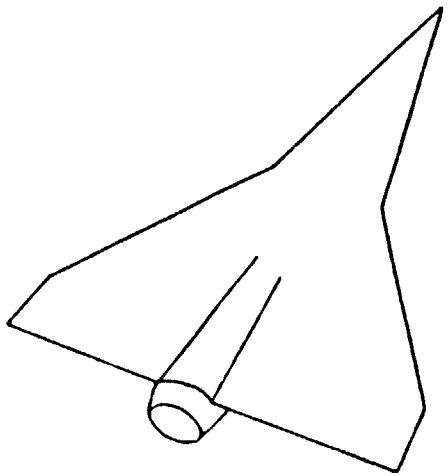
FLOW PHYSICS

- MULTIPLE INTERACTING VORTICES
- FLOW ASYMMETRY
- STREAMWISE AND CROSS-FLOW SHOCKS
- VORTEX/SHOCK UNSTEADINESS
- BURSTING

WIND TUNNEL MODELS

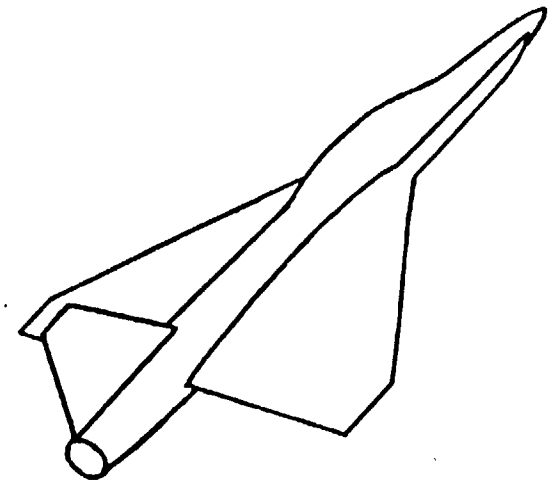
- SIMPLE GEOMETRIES TO MINIMIZE GRID-GENERATION DIFFICULTIES

LEX/DELTA



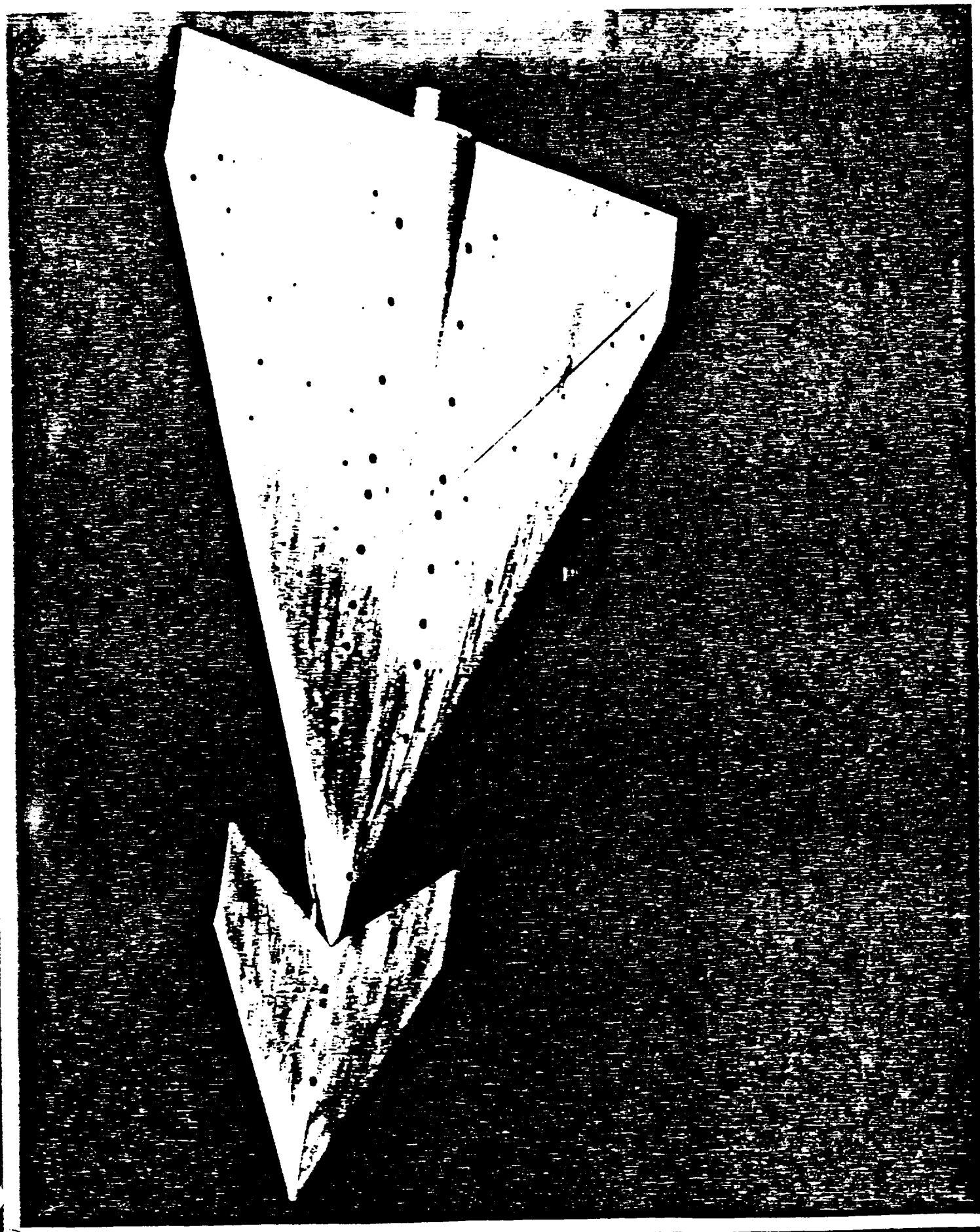
PLANNED

GENERIC FIGHTER



CURRENT
- VARIOUS CHINES
- LE/TE FLAPS

- FULL-SPAN MODELS
- SHARP/ROUND WING LE'S



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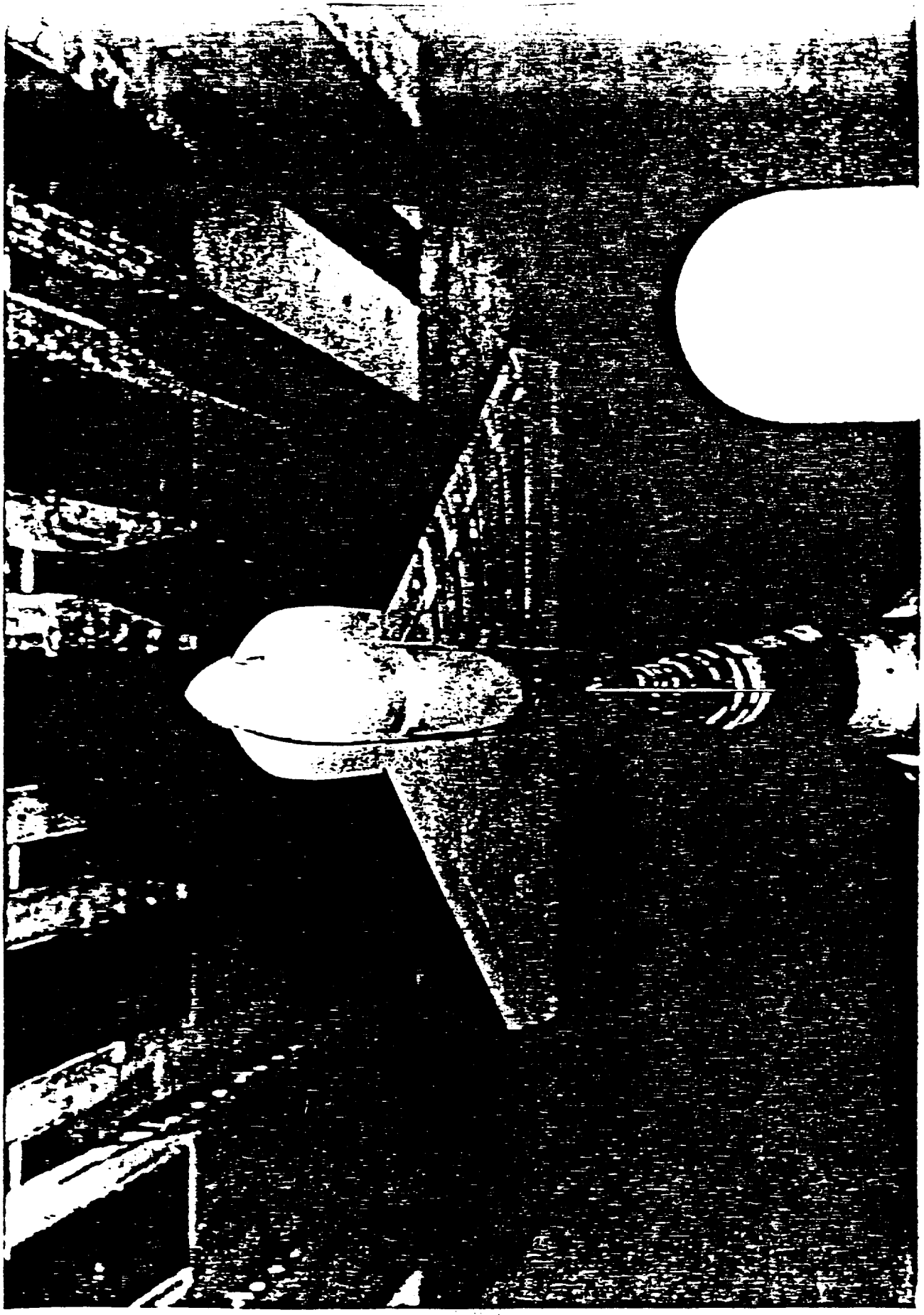

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WIND TUNNELS

- LARGE TRANSONIC/SUPERSONIC WIND TUNNELS
  - NAVY 7X10 TRANSONIC TUNNEL $0.4 \leq M_\infty \leq 1.2$
  - AMES 6X6 SUPERSONIC TUNNEL $0.25 \leq M_\infty \leq 2.2$
- SLOTTED WALLS
- GOOD OPTICAL ACCESS FOR LASERS
- REYNOLDS NUMBER APPROXIMATELY 2 TO 7 MILLION
- STING-MOUNTED FULL-SPAN MODELS

STAFF

- EXPERIMENTAL
  - Gary Erickson
  - John Schreiner
- COMPUTATIONAL
  - Aga Goodsell
  - Steve Smith

EXPERIMENTS

- FLOW CONDITIONS
  $0.4 \leq M_\infty \leq 1.8, \quad 0^\circ \leq \alpha \leq 30^\circ, \quad -15^\circ \leq \beta \leq 15^\circ$

- SURFACE PRESSURES, FORCES & MOMENTS

- OFF-BODY AND SURFACE FLOW VISUALIZATION
  - VORTEX AND SHOCK LOCATIONS
  - BURST LOCATIONS
  - SECONDARY SEPARATION LINE
  - BOUNDARY LAYER TRANSITION

- INSTRUMENTATION
  - PSI MODULES FOR SURFACE C_p
  - SIX-COMPONENT INTERNAL BALANCE
  - OIL FLOW, MINI-TUFTS
  - 18-WATT LASER FOR VAPOR SCREEN & 2-D/3-D LDV

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COMPUTATIONS

- EULER AND NAVIER-STOKES (FLO-57, TNS CODES)
- PARAMETER VARIATIONS
  - GRID ARRANGEMENT AND EXTENT
  - GRID DENSITY
  - DAMPING LEVELS
- ASSESS EULER AND NAVIER-STOKES SUBCRITICAL ATTACHED-FLOW SOLUTIONS WITH POTENTIAL-FLOW SOLUTIONS

LIMITATIONS/UNCERTAINTIES

EXPERIMENTAL

- WALL/STING EFFECTS
- FLOW QUALITY
- MEASUREMENT ACCURACY
- GEOMETRIC ACCURACY

COMPUTATIONAL

- SPECIFIED TRANSITION POINTS
- TURBULENCE MODEL
- NUMERICS
  - NONPHYSICAL VISCOSITY
  - FALSE ENTROPY
- GEOMETRIC ACCURACY

SUMMARY

- FIGHTER-LIKE VORTICAL FLOW PHYSICS
- COMPARATIVELY SIMPLE GEOMETRIES
- LARGE TRANSONIC/SUPERSONIC WIND TUNNELS
- SURFACE AND FLOW-FIELD MEASUREMENTS
- FORCES/MOMENTS FROM INTERNAL BALANCE
- EULER AND NAVIER-STOKES CODES

HYPERSONIC FLOW CODE VALIDATION ACTIVITY

REAL GAS FLOWS

Thermosciences Division
NASA Ames Research Center

NASA CFD VALIDATION WORKSHOP

JULY 14-16, 1987

George S. Deiwert, Chief, Aerothermodyamics Branch

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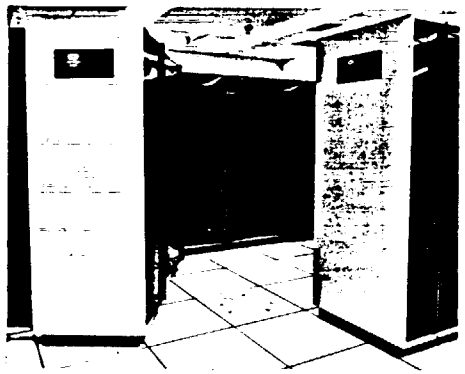
N92-70928

Ame Research Center

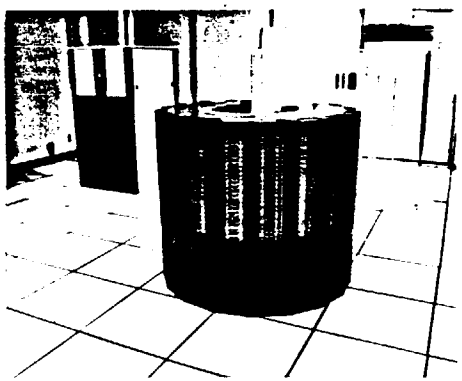
FACILITIES FOR STUDIES IN HYPERSONICS AND ENTRY TECHNOLOGY

COMPUTERS



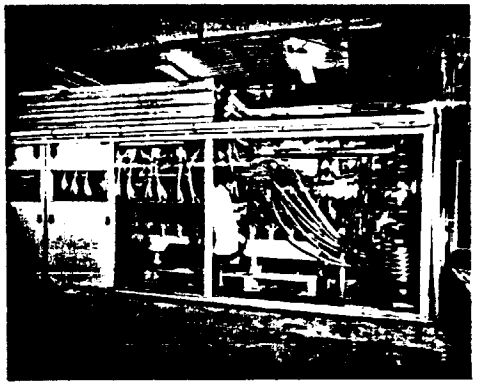
CYBER 205

CRAY XMP/48

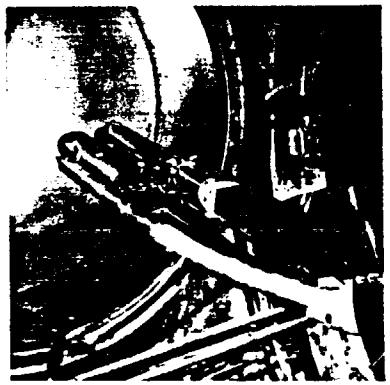


NAS

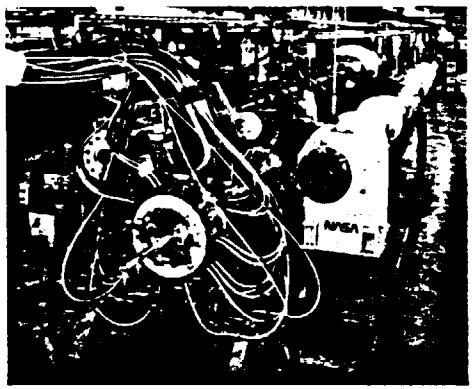
GROUND-BASED AND FLIGHT EXPERIMENTS



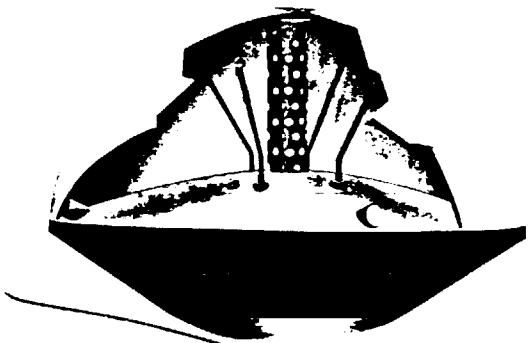
ARC JETS



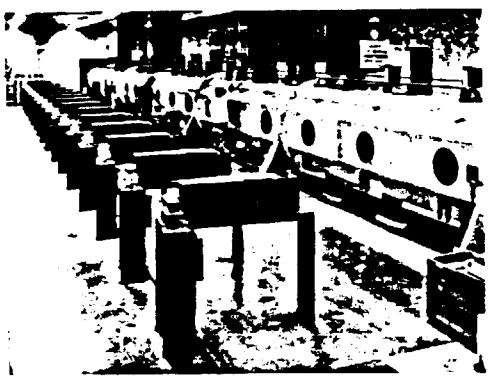
3.5-FOOT HYPERSONIC WIND TUNNEL



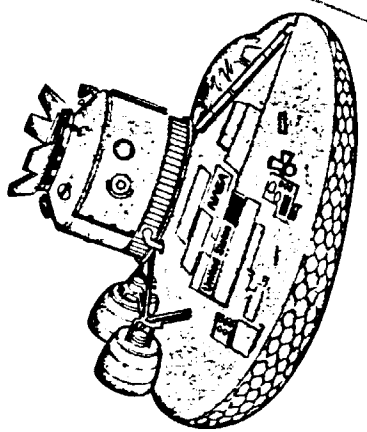
SHOCK TUBES



PAET

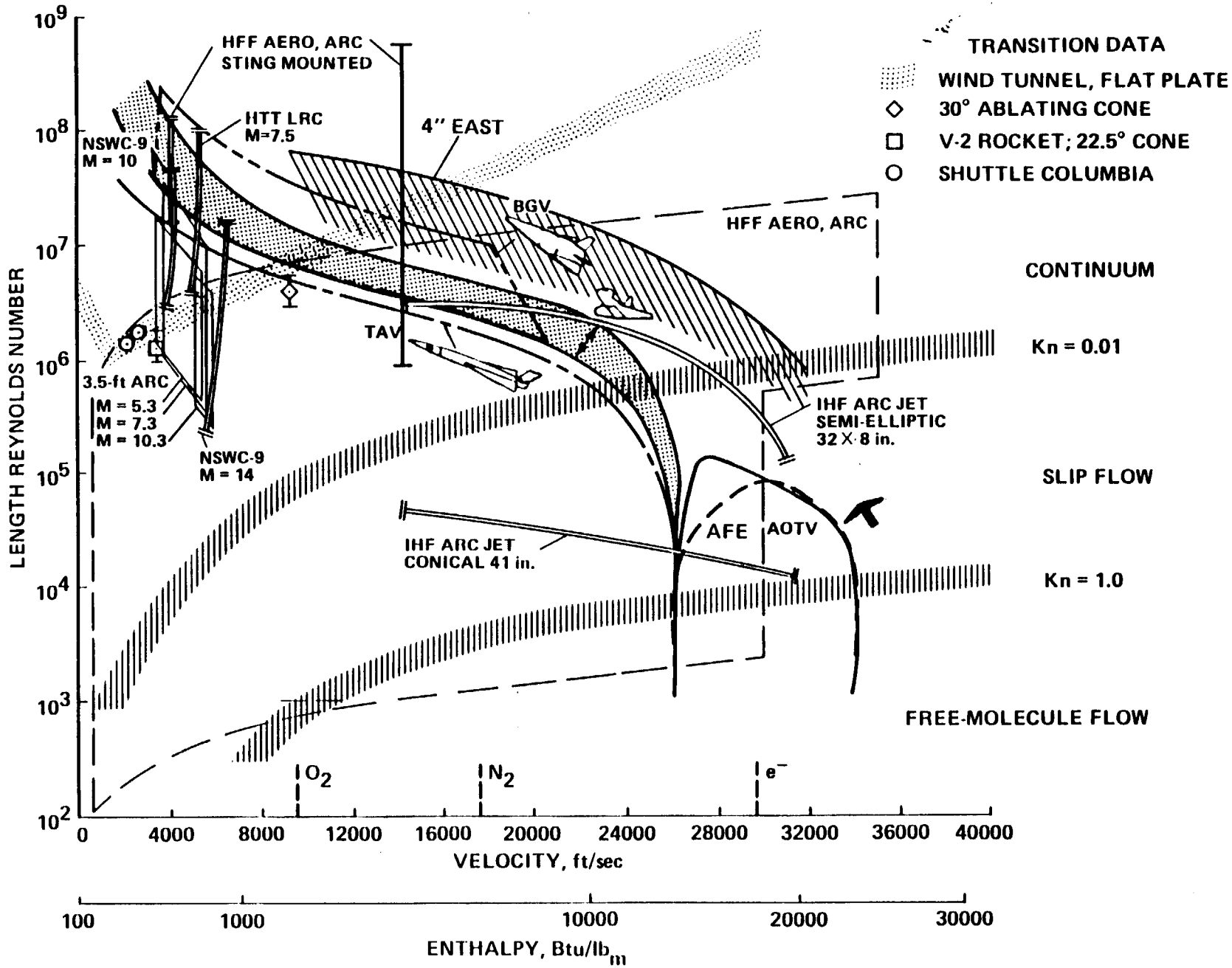


BALLISTIC RANGES



AFE

SIMULATION CAPABILITY



HYPERSONIC FLOW CODE VALIDATION ACTIVITY

CODE	VALIDATION ACTIVITY	FACILITY
PERFECT GAS	GENERIC TAV CONFIGURATIONS AOTV CONFIGURATIONS	3.5' HWT PRESSURIZED BALLISTIC RANGE
REAL GAS	CONES AND BLUNT BODIES BLUNT BODY SHOCK LAYER BENCHMARK CODES	HFFAF (BALLISTIC RANGE) SHOCK TUBES CCF AND NAS
NOZZLE/PLUME	MULTI-NOZZLE PERFECT GAS SEMI DIRECT CONNECT TEST	3.5' HWT HFFAF (16" SHOCK TUNNEL)
COMBUSTION	OBLIQUE DETONATION WAVE	20 MW ARCJET
THERMOCHEMICAL NONEQUILIBRIUM	SHOCK TUBE DATA SHOCK LAYER DATA FLIGHT EXPERIMENT	E.A.S.T. HFFAF AND 60 MW ARCJET AFE
BOUNDARY LAYER AND TRANSITION	TUNNEL WALL BOUNDARY LAYER TRANSITION ON CONES	HFFAF (16" SHOCK TUNNEL) HFFAF (BALLISTIC RANGE)

VALIDATION SCENARIO

	BUILDING BLOCK	BENCH MARK	DESIGN
PERFECT	○ ○ ○ ○ ○ ×	● ○ ○ ○ ○ ○ ×	● ○ ○ ○ ○ ×
EQUILIBRIUM	□ □ □ □ ● ×	■ □ □ □ ● ×	■ □ □ □ ● ×
NONEQUILIBRIUM	△ △ △ ■ ×	▲ △ △ ■ ×	▲ △ △ ■ ×

○□△ EXPERIMENTS
●■▲ EXPERIMENTS AND COMPUTATIONS
× VALIDATED CODES

HYPERSONIC PERFECT GAS FLOWS

(UPWIND NAVIER-STOKES AND PARABOLIZED NAVIER STOKES)

- GENERIC TAV CONFIGURATIONS

FACILITY:	3.5ft HWT
FLOW CONDITIONS:	$5 < M < 14$, $1.5 \times 10^6 < Re_L < 25 \times 10^6$, alt $< 210{,}000$ ft
DATA TAKEN:	SURFACE PRESSURES AND HEAT FLUX
	SURFACE STREAMLINES (OIL FLOW PATTERNS)
	SHADOWGRAPH (SHOCKS AND SHEAR LAYERS)
	LDV FLOW FIELD SURVEYS

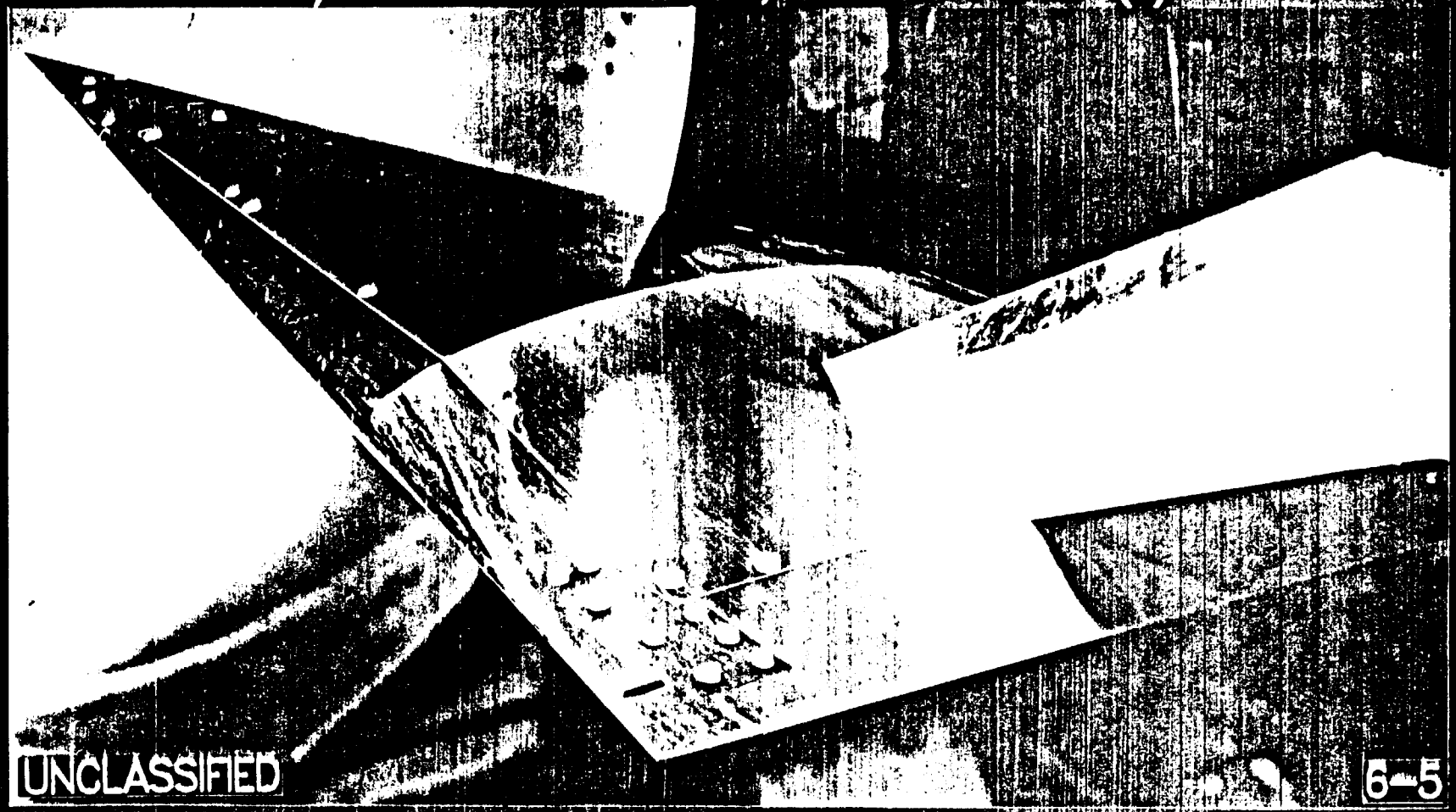
- AOTV (AFE) CONFIGURATIONS

FACILITY:	PRESSURIZED BALLISTIC RANGE
FLOW CONDITIONS:	$V = 5000$ fps, $Re_D = 50{,}000$, $M = 4.5$
DATA TAKEN:	SHADOWGRAPH (SHOCKS AND SHEAR LAYERS)
	TOTAL DRAG AND PITCHING MOMENT

UNCLASSIFIED

ALL-BODY HYPERSONIC AIRCRAFT MODEL IN NASA/AMES 3.5-FT HWT (U)

W/O CONTROL SURFACES; LENGTH = 3 FT (U)

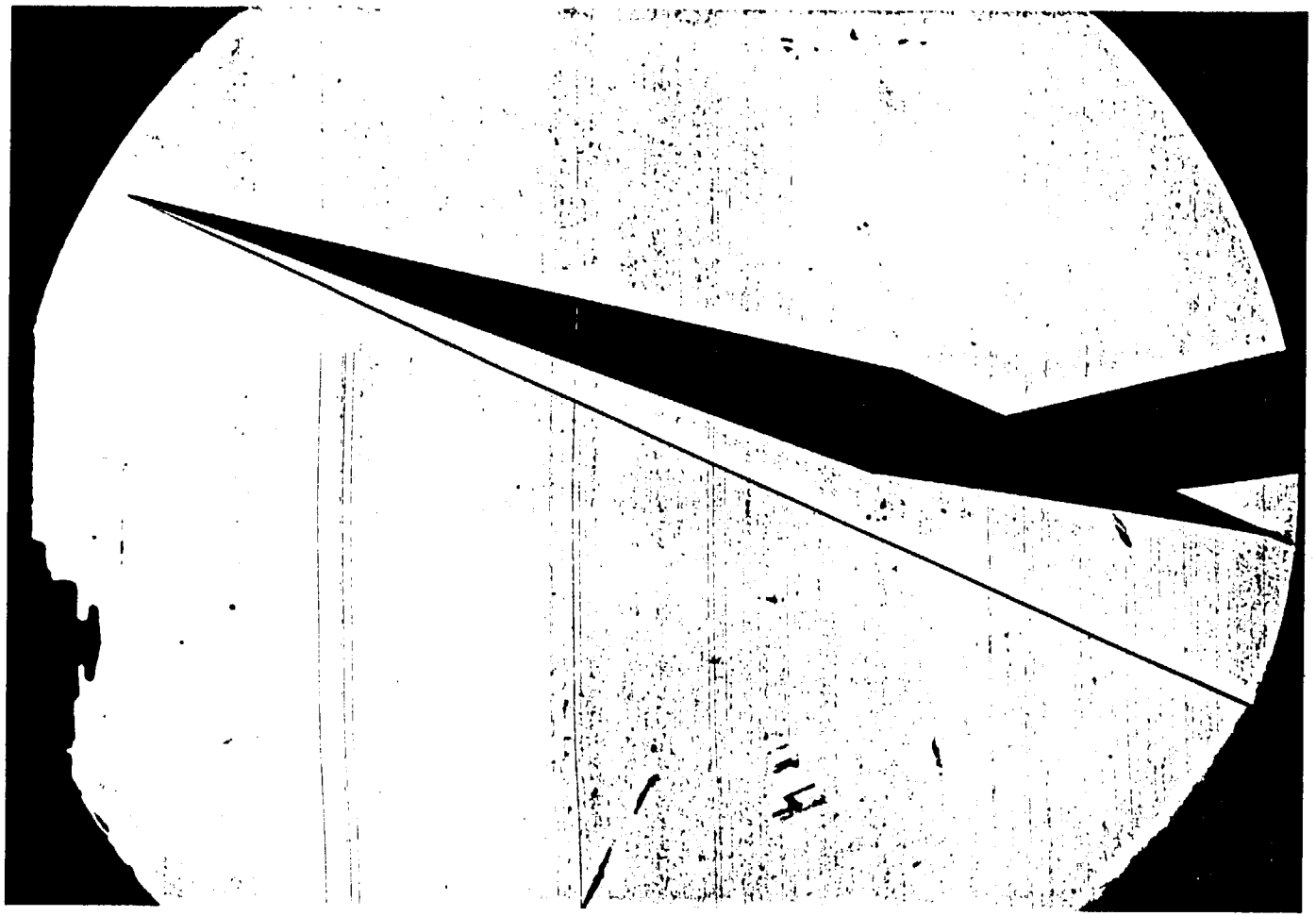


UNCLASSIFIED

ALL–BODY MODEL SHADOWGRAPH

$\alpha = 15^\circ$

$M_\infty = 7.4$; $Re_{\infty,L} = 15 \times 10^6$



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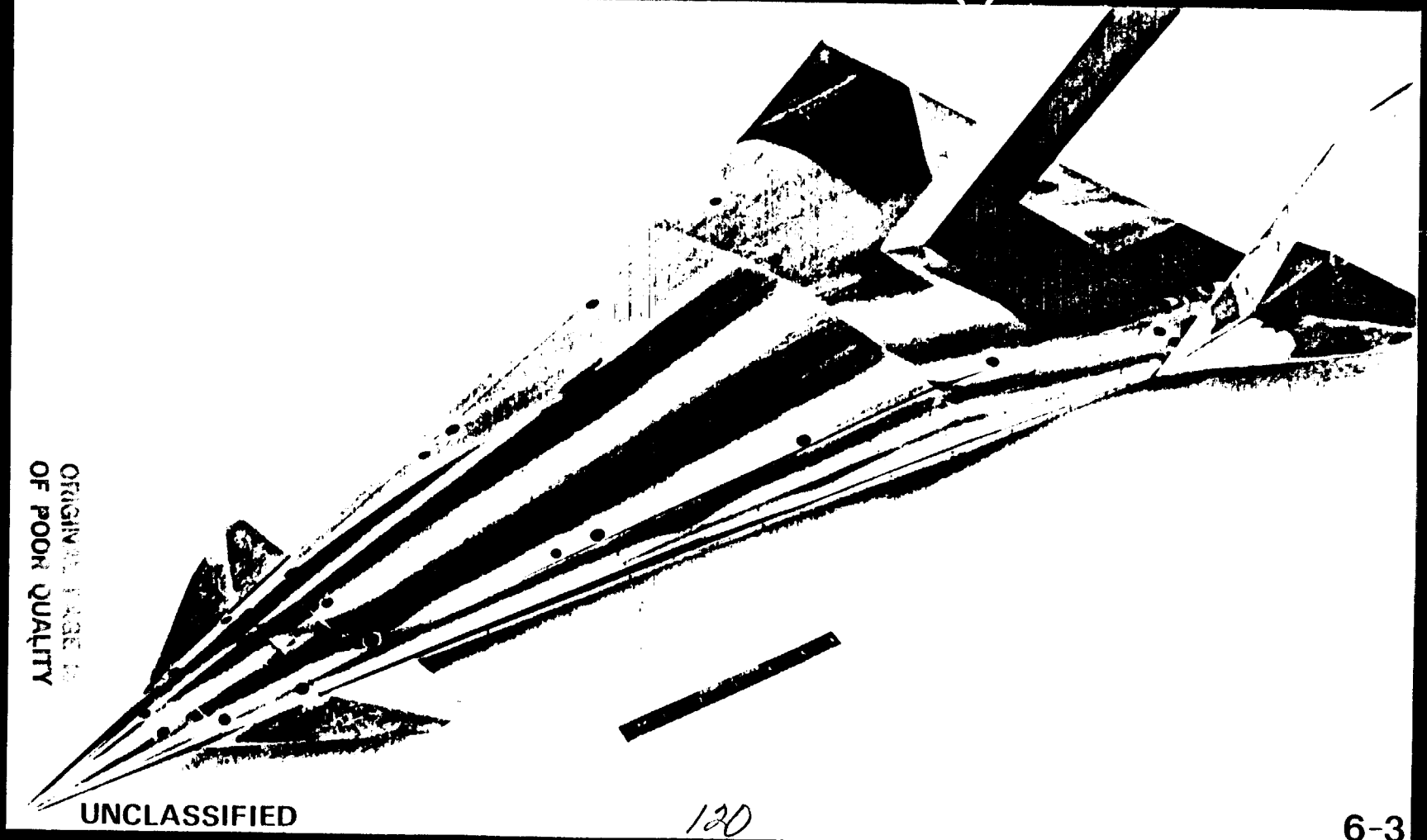
NASA/Ames RTA Lockman

ALL-BODY HYPERSONIC AIRCRAFT MODEL (U)
WITH CONTROL SURFACES (U)



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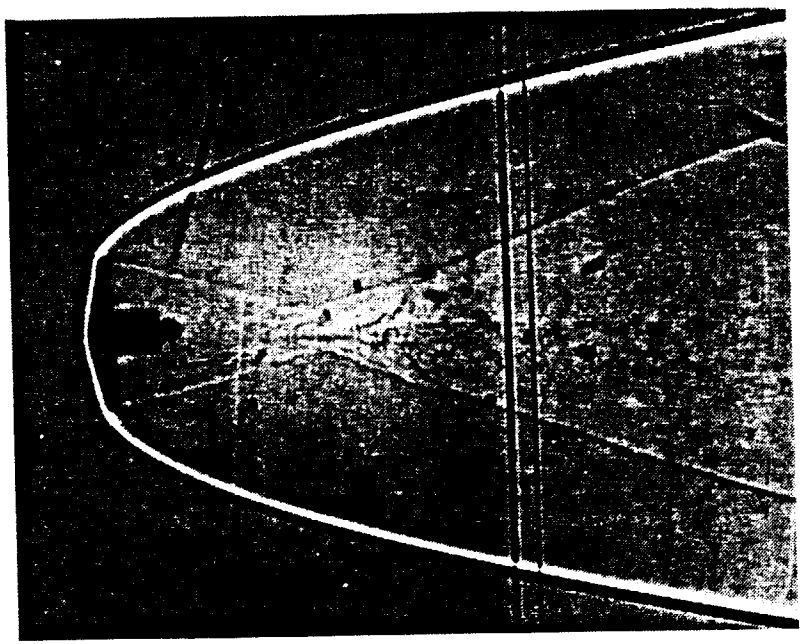
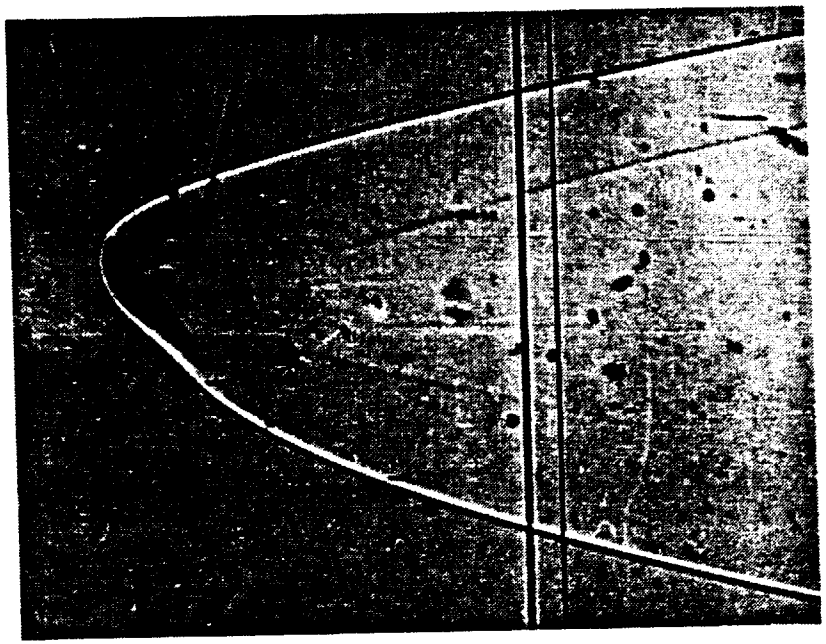
BALLISTIC RANGE SHADOWGRAPHS FOR TWO AOTV CONFIGURATIONS

SYMMETRIC DRAG BRAKE



RAKED ELLIPTIC CONE



HYPERSONIC REAL GAS FLOWS

(REAL GAS UPWIND AND PARABOLIZED NAVIER-STOKES)

- SHARP AND BLUNT CONES, BICONICS, BLUNT BODIES

FACILITY:	HFFAF (BALLISTIC RANGE)
FLOW CONDITIONS:	$15 < M < 30$, $10^3 < Re < 10^7$, $V_{max} = 30{,}000$ fps
DATA TAKEN:	SHADOWGRAPH (SHOCKS AND SHEAR LAYERS) HOLOGRAMS (DENSITY FIELD) DRAG AND PITCHING MOMENT

- BLUNT BODY SHOCK STRUCTURE

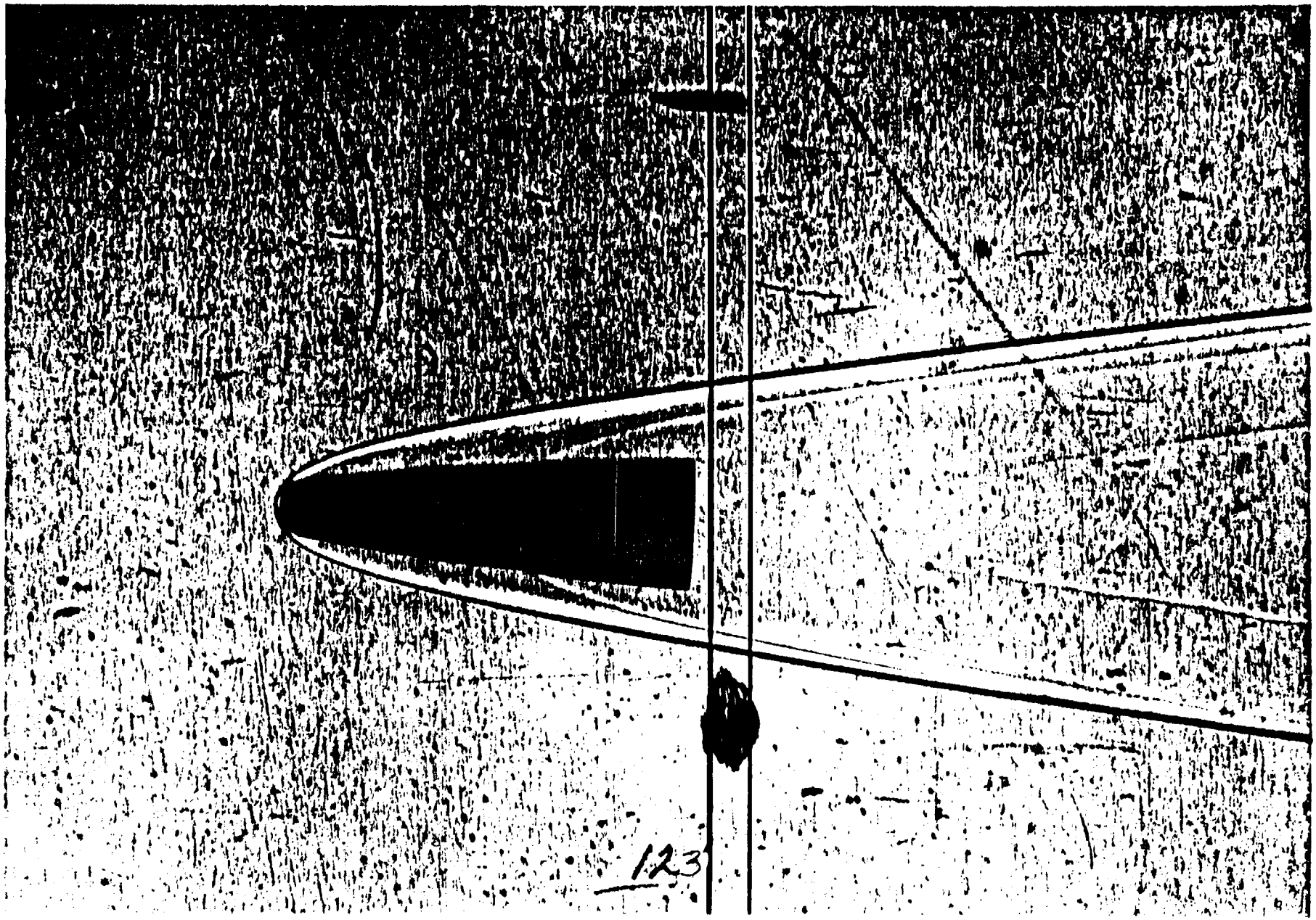
FACILITY:	2 INCH SHOCK TUBE
FLOW CONDITIONS:	$M = 2$, $Re = 10^6$, $H_o = 25$ MJ/kg
DATA TAKEN:	SHADOWGRAPH, SCHLIEREN, INTERFEROGRAMS

- BENCHMARK THERMOCHEMICAL NONEQUILIBRIUM FLOW SIMULATIONS

  ONE AND TWO DIMENSIONAL SIMULATIONS WITH VALIDATED, FULLY COUPLED THERMOCHEMICAL NONEQUILIBRIUM FLOW CODES (e.g. STRAP, SPRAP)

BLUNT BICONIC

$M = 14.4$, $V = 16{,}350$ fps, $Re_L = 3 \times 10^6$, $p = 110$ torr
(HFFAF)



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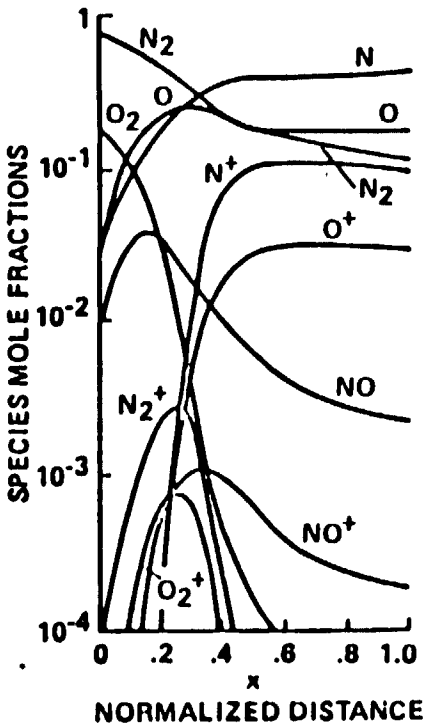
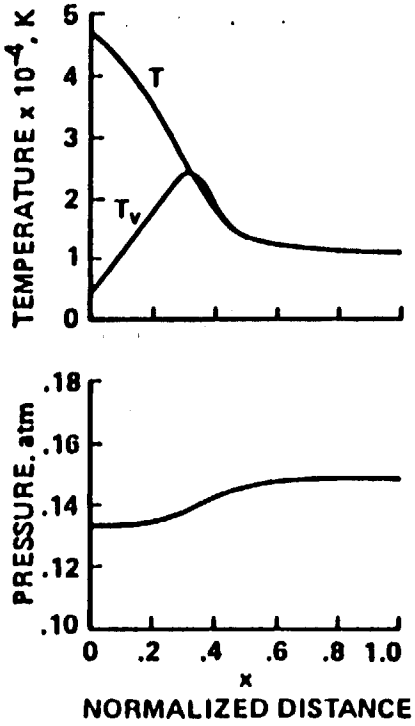
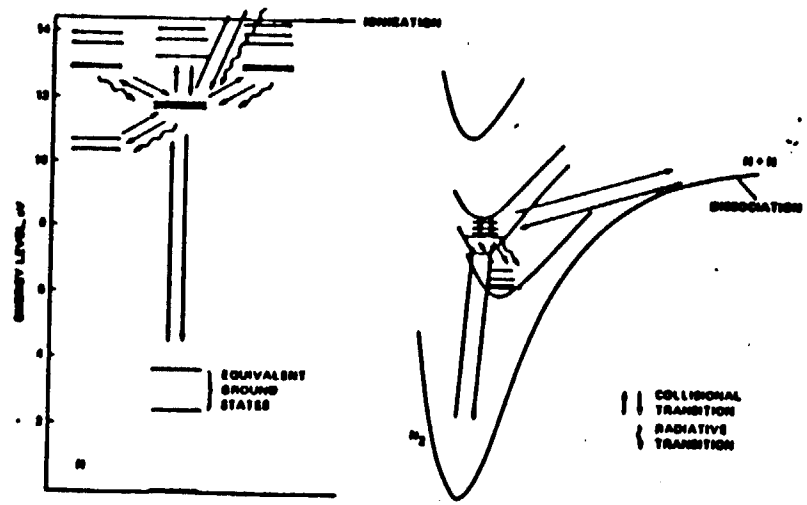
FLUID AND AEROTHERMODYNAMIC FORCES

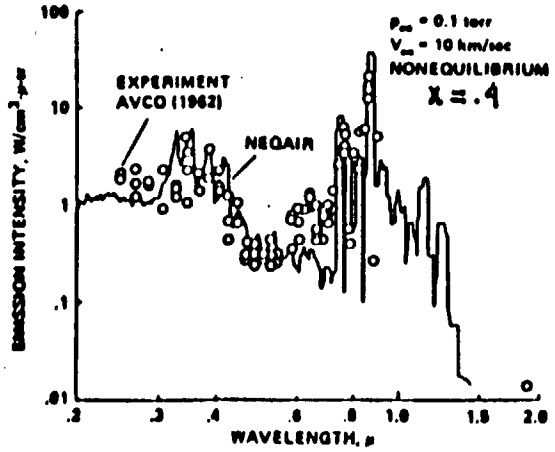
EXTERNAL FLOW - NONEQUILIBRIUM

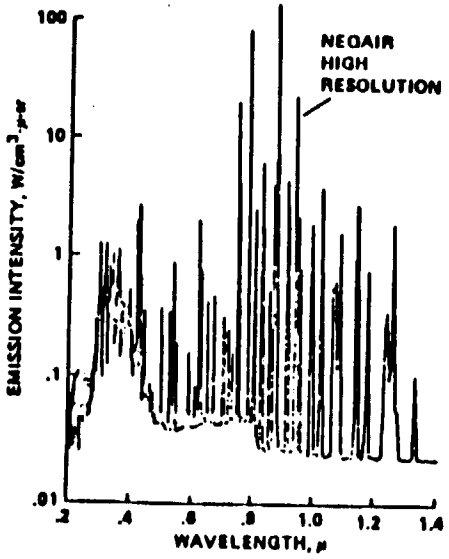
COMPARISON BETWEEN CALCULATED AND MEASURED SPECTRA
NON EQUILIBRIUM FLOW BEHIND A SHOCK, V = 10 km/s, P = 0.1 torr

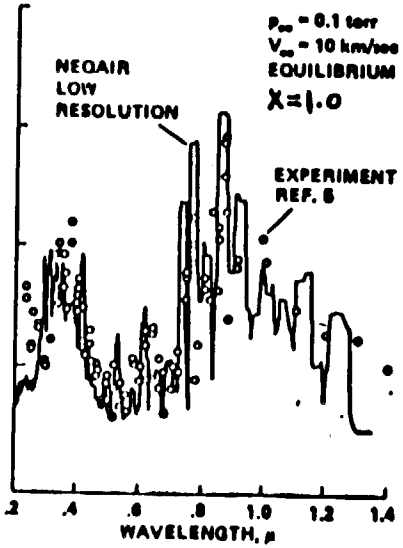












NOZZLE/PLUME FLOWS

(REAL GAS UPWIND NAVIER-STOKES)

- MULTI-NOZZLE CONFIGURATIONS – PERFECT GAS FLOWS

FACILITY:	3.5' HWT
FLOW CONDITIONS:	$5 < M < 14$, $.5 \times 10^6 < Re/L < 8 \times 10^6$ /ft
DATA TAKEN:	SURFACE PRESSURE AND HEAT FLUX SURFACE STREAMLINES (OIL FLOW PATTERNS) SHADOWGRAPH (SHOCKS AND SHEAR LAYERS) LDV FLOW FIELD SURVEYS

- SEMI-DIRECT CONNECT HYPERSONIC NOZZLE TEST

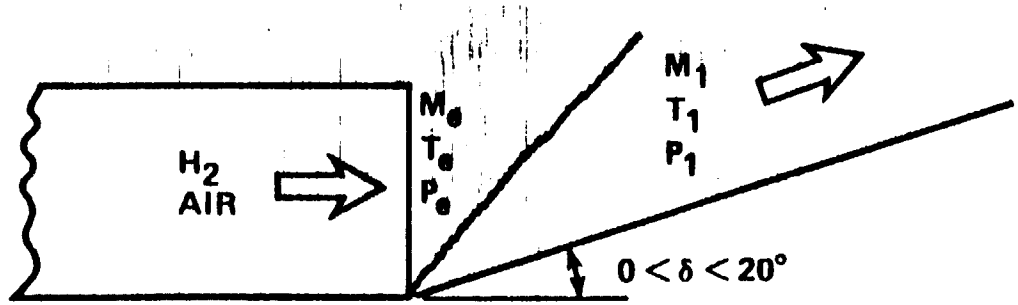
FACILITY:	16" SHOCK TUNNEL (HFFAF), 45 sec FLOW TIME
FLOW CONDITIONS:	$M = 7$, $H_o = 3000$ Btu/lb, $0.005 < p_s < 2$ atm, $Re/L = 6 \times 10^6$/ft
DATA TAKEN:	SPECIES AND DENSITY DISTRIBUTIONS (LIF, CARS) SHADOWGRAPHS (SHOCKS AND SHEAR LAYERS) THRUST

COMBUSTION/DETONATION

(HYDROGEN-AIR COMBUSTION NAVIER-STOKES CODES)

- OBLIQUE DETONATION WAVE IN HYDROGEN-AIR MIXTURES

FACILITY:	20 MW ARCJET
FLOW CONDITIONS:	$M_e = 4.5$, $H_o = 4.5$ MJ/kg, $p_e = 0.016$ atm, $T_e < 1500$ K
DATA TAKEN:	SURFACE PRESSURES AND HEAT FLUX SPECTROGRAPHIC DATA (SPECIES) PHOTOGRAPHIC DATA (SHOCKS AND DETONATION WAVES)



THERMOCHEMICAL NONEQUILIBRIUM

(MULTI-TEMPERATURE NONEQUILIBRIUM NAVIER-STOKES CODES)

- **SHOCK TUBE DATA**

FACILITY:	E.A.S.T. (ELECTRIC ARC DRIVEN SHOCK TUBE)
FLOW CONDITIONS:	$5 < U_s < 13$ km/sec, $.05 < p_1 < 1$ torr
DATA TAKEN:	SPECTRAL DATA, SPECIES, VIBRATIONAL ENERGY (LIF, CARS)

- **SHOCK LAYER DATA**

FACILITY:	HFFAF
FLOW CONDITIONS:	$15 < M < 30$, $1 < p < 15$ torr
DATA TAKEN:	HOLOGRAMS, SHADOWGRAPHS (DENSITY, SHOCKS)
FACILITY:	60 MW ARCJET
FLOW CONDITIONS:	$M = 8$, $p_0 = .012$ atm, $H_0 = 46$ MJ/kg
DATA TAKEN:	SPECTRAL DATA (SPECIES DISTRIBUTIONS)

- **AFE, FLIGHT EXPERIMENT FOR AOTV**

FLOW CONDITIONS:	$8 < V < 10$ km/sec, $70 < h < 120$ km
DATA TAKEN:	RADIATION SPECTRA, SPECIES DISTRIBUTION, SURFACE p & q

NONEQUILIBRIUM RADIATION

(NEQAIR)

- SHOCK TUBE DATA

FACILITY:	E.A.S.T.
FLOW CONDITIONS:	$5 < V_s < 13$ km/sec, $0.05 < p_1 < 1$ torr
DATA TAKEN:	SPECTRAL DATA, NONEQUILIBRIUM RADIATION

- AFE, FLIGHT EXPERIMENT FOR AOTV

FLOW CONDITIONS:	$8 < V < 10$ km/sec, $70 < h < 120$ km
DATA TAKEN:	RADIATION SPECTRA, TOTAL RADIANCE (0.2μ TO 0.8μ) (0.2μ TO 2μ)

HYPERSONIC BOUNDARY LAYER AND TRANSITION

- TUNNEL WALL BOUNDARY LAYER GROWTH

FACILITY:	16" SHOCK TUNNEL (HFFAF)
FLOW CONDITIONS:	$M = 7$, $Re/ft = 6 - 80 \times 10^6$, $L = 90$ ft
DATA TAKEN:	FLOW FIELD SURVEY (LIF, CARS) SPECIES AND DENSITY DIST. TOTAL PRESSURE AND TEMPERATURE, STATIC PRESSURE HOLOGRAPHY

- TRANSITION STUDIES ON CONES

FACILITY:	HFFAF (BALLISTIC RANGE)
FLOW CONDITIONS:	$15 < M < 30$, $10^3 < Re < 10^7$
DATA TAKEN:	SHADOWGRAPH AND TOTAL DRAG

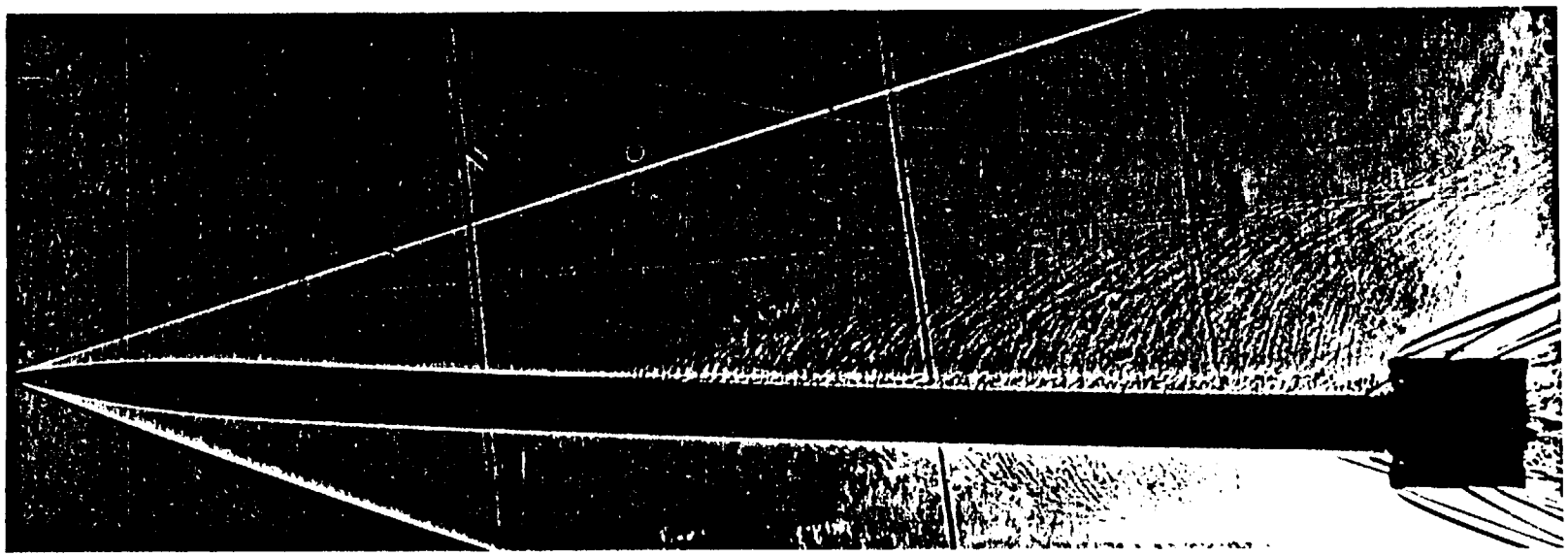
AMES RESEARCH CENTER HYPERSONIC FACILITIES
HYPERSONIC FREE FLIGHT FACILITY TEST CONDITIONS

• STREAM	
– MACH NUMBER	7 (OR STILL AIR)
– STATIC PRESSURE	0.005 TO 2 atm
– ENTHALPY, max.	3000 Btu/lb
• REYNOLDS NUMBER	80,000,000 ft^{-1}
• MODEL	
– VELOCITY, max.	30,000 ft/sec
– ACCELERATION, max.	1,500,000 g
– SIZE, max.	37 mm diam
– WEIGHT, max.	45 g
• INSTRUMENTED RANGE SECTION	
– DIAMETER	3.5 ft
– LENGTH	75 ft
– NUMBER OF STATIONS	16

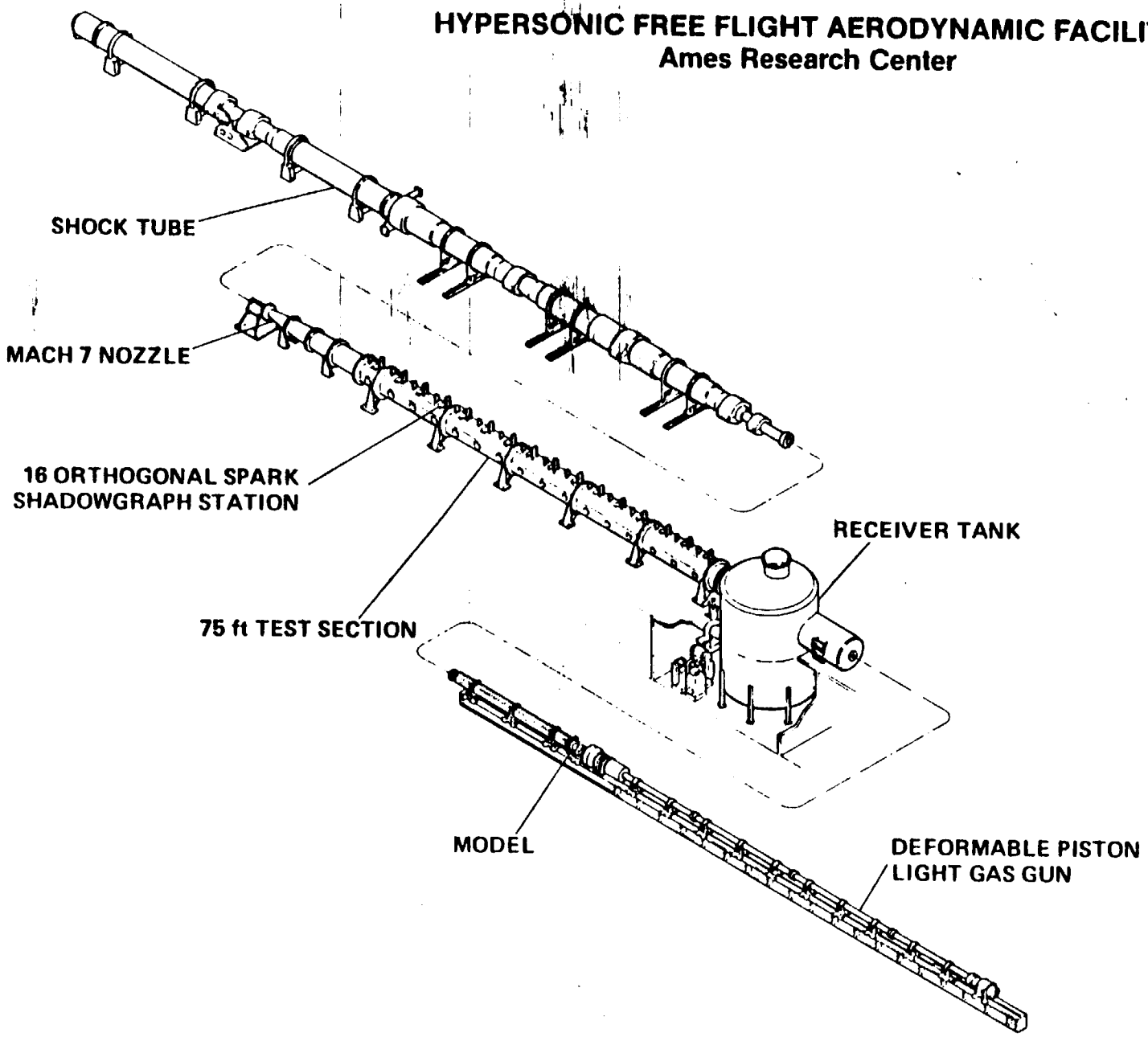
BOUNDARY LAYER TRANSITION

PRESSURIZED BALLISTIC RANGE

$M_\infty = 3.5$, $Re/x = 2 \times 10^6$/in., $L = 6$ in.



HYPERSONIC FREE FLIGHT AERODYNAMIC FACILITY
Ames Research Center



AMES RESEARCH CENTER HYPERSONIC FACILITIES PRESSURIZED BALLISTIC RANGE TEST CONDITIONS

• STATIC RANGE CONDITIONS	
– GAS COMPOSITION	AIR
– PRESSURE	0.1 TO 1 atm
– TEMPERATURE	AMBIENT
• REYNOLDS NUMBER, max.	40,000,000 ft^{-1}
• MODEL	
– VELOCITY, max.	11,000 ft/sec
– ACCELERATION, max.	1,000,000 g
– SIZE, max.	57 mm diam
– WEIGHT, max.	100 g
• INSTRUMENTED RANGE SECTION	
– LENGTH	203 ft
– SIZE, max.	20 in. WIDE X 20-60 in. HIGH
– NUMBER OF STATIONS	24

ELECTRIC ARC SHOCK TUBE

	4 in. TUBE	24 in. TUBE
LENGTH	40 ft	70 ft
SHOCK VELOCITY	35 km/sec	13 km/sec
REFLECTED SHOCK PRESSURE	10,000 psi	30 psi
NOZZLE	M ≈ 15	NONE
APPLICATIONS	RADIATION AND IONIZATION STUDIES, CHEMICAL REACTION RATE MEASUREMENTS, DIAGNOSTICS IN HIGH ENERGY FLOWS.	

AMES RESEARCH CENTER HYPERSONIC FACILITIES
3.5-FOOT HYPERSONIC WIND TUNNEL TEST CONDITIONS

- MACH NUMBER = 5.3
  - RESERVOIR TEMPERATURE — 1200 TO 2500°R
  - RESERVOIR PRESSURE — 50 TO 400 psia
  - UNIT REYNOLDS NUMBER — 200,000 TO 5,600,000 ft^{-1}
  - EQUIVALENT PRESSURE ALTITUDE — 60,000 TO 120,000 ft
- MACH NUMBER = 7.4
  - RESERVOIR TEMPERATURE — 1200 TO 2500°R (DESIGN LIMIT 3460°R)
  - RESERVOIR PRESSURE — 200 TO 2000 psia
  - UNIT REYNOLDS NUMBER — 300,000 TO 8,000,000 ft^{-1}
  - EQUIVALENT PRESSURE ALTITUDE — 85,000 TO 140,000 ft
- MACH NUMBER = 10.4
  - RESERVOIR TEMPERATURE — 2000 TO 2300°R (DESIGN LIMIT 3460°R)
  - RESERVOIR PRESSURE — 400 TO 2000 psia
  - UNIT REYNOLDS NUMBER — 400,000 TO 1,900,000 ft^{-1}
  - EQUIVALENT PRESSURE ALTITUDE — 140,000 TO 190,000 ft
- MACH NUMBER = 14 (NOT OPERATIONAL)
  - RESERVOIR TEMPERATURE — 3460°R
  - RESERVOIR PRESSURE — 2000 psia
  - UNIT REYNOLDS NUMBER — 250,000 ft^{-1}
  - EQUIVALENT PRESSURE ALTITUDE — 210,000 ft

AMES RESEARCH CENTER HYPERSONIC FACILITIES

AMES ARC-JET CAPABILITIES

FACILITY	GAS	INPUT POWER MW	TYPE OF TEST ARTICLE	NOZZLE EXIT DIMENSIONS inches	M	SAMPLE SIZE inches	BULK ENTHALPY Btu/lb	SURF. PRESS. atm	CONVECTIVE HEATING RATE Btu/ft^2 sec	RADIATIVE HEATING RATE Btu/ft^2 sec
AERO HEATING	AIR	20	STAG PT.	CONICAL	2.5-12	8" dia.	14,000	.005-2	0.5-300	0
			WEDGE	3,7,12,18,24 36, 42" diam		26 X 26		.001	0.5-22	0
2" X 9" DUCT	AIR	20	FLAT PLATE	2-DIMENSION	3.5	8 X 20	4,000	0.02-0.15	2-60	0
PANEL TEST FACILITY	AIR	20	WEDGE	SEMIELLIPTIC 4" X 18"	5.5	16 X 16	15,000	.0005-.05	0.5-75	0
INTERACTION HEATING FACILITY	AIR	60	WEDGE	SEMIELLIPTIC 8" X 32"	5.5	24 X 24	20,000	0001-.015	0.5-30	0-5
			STAG PT.	CONICAL 36" diam	7.5	18" diam		.010-.1	5-130	0-10
GIANT PLANET	H_2/HE N_2	75	STAG PT.	CONICAL 2.75" diam	1.7	1.6 diam	100,000	0.5-2.7	14,500	7,000
HI ENTHALPY ENTRY FACILITY	H_2/HE N_2	120	STAG PT.	CONICAL 4" diam	1.7	2.3 diam	100,000	2	14,500	12,000

N92-70929

AGENDA

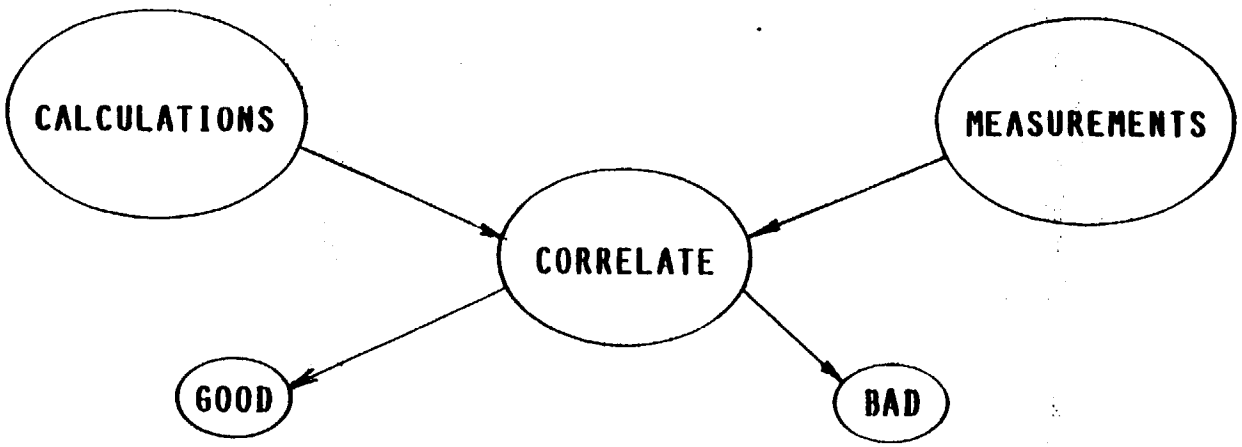
- DEFINITIONS
- ERROR SOURCES
- WIND TUNNELS AND SMALL TEST FACILITIES
- INSTRUMENTATION
- EXAMPLES OF CODE VALIDATION RESEARCH
- CONCLUDING REMARKS

P J Bobbitt, LaRC

CODE VALIDATION

VALIDATE - 1. TO MAKE VALID; TO GIVE LEGAL FORCE TO, 2. TO TEST OR PROVE THE VALIDITY OF; TO CONFIRM.

****
* TO VALIDATE A CODE IS TO MAKE ITS RESULTS BELIEVABLE--TO GIVE *
* CONFIDENCE THAT ITS RESULTS ARE ACCURATE. *
****



VALIDATED

GO TO HIGHER ORDER THEORY
GO TO DIFFERENT SOLUTION TECHNIQUE
GO TO BETTER PHYSICAL MODEL
GO TO MORE ACCURATE EXPERIMENT OR A DIFFERENT TUNNEL

CODE "CALIBRATION"

CALIBRATION - TO DETERMINE THE SCALE FACTORS AND TARES FOR ACCURATE MEASUREMENT.
TO DETERMINE A FUDGE FACTOR TO EFFECT AN AGREEMENT BETWEEN TWO RESULTS.

COULD BE INTERPRETED TO MEAN HOW WELL A CODE WORKS VERSUS THE EXPERIMENTAL "STANDARD" IF ONE STRETCHES THE DEFINITION

```
*****************************************
*            "CALIBRATION"              *
*                                       *
*    NOT APPROPRIATE WORD FOR THE TYPE  *
*    OF EXPERIMENTAL RESEARCH WE DO TO  *
*    VALIDATE CODES                     *
*****************************************
```

WIND TUNNEL ERROR SOURCES

- INSTRUMENTATION
- WALL EFFECTS
- STING EFFECTS
- AEROELASTICITY
- GEOMETRY DEFINITION
- SURFACE FINISH
- FLOW QUALITY/NOISE
- FLOW UNIFORMITY
- REYNOLDS NUMBER

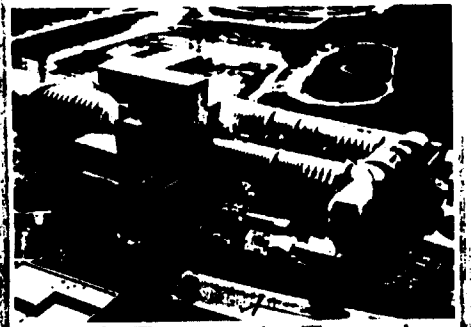
[redacted]

COMPUTATIONAL ERRORS

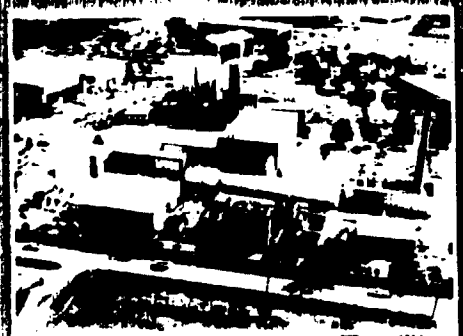
- GRID RESOLUTION
- UNIQUENESS
- GRID ASPECT RATIO/GRID IRREGULARITIES
- ARTIFICIAL VISCOSITY
- MATH MODEL/EQUATION SET
- GEOMETRY REPRESENTATION
- BOUNDARY CONDITIONS
- ROUND OFF ERROR/TRUNCATION ERROR
- SOLUTION NOT CONVERGED
- TURBULENCE MODEL
- BUGS

MAJOR RESEARCH TUNNELS

Transonic Aerodynamics Division

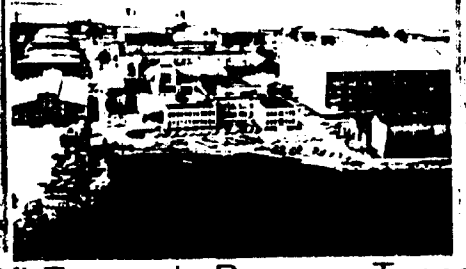


16ft Transonic Tunnel

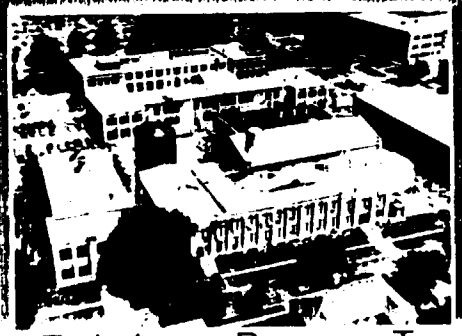


National Transonic Facility

7x10ft High Speed Tunnel



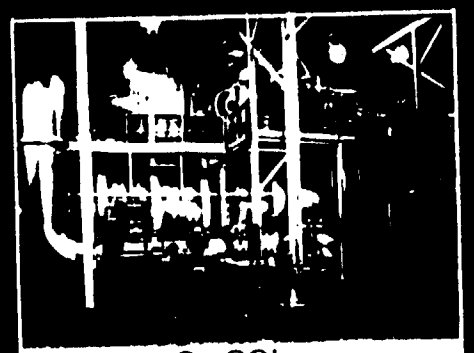
8ft Transonic Pressure Tunnel



Low Turbulence Pressure Tunnel

SMALL RESEARCH TUNNELS

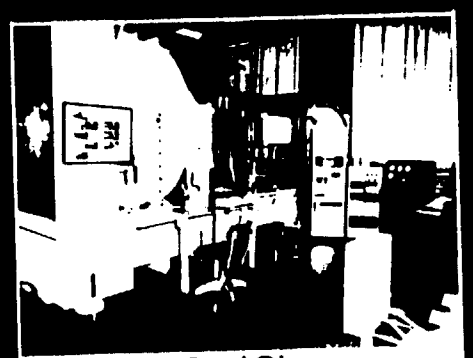
Transonic Aerodynamics Division



6x28in.
Transonic Tunnel

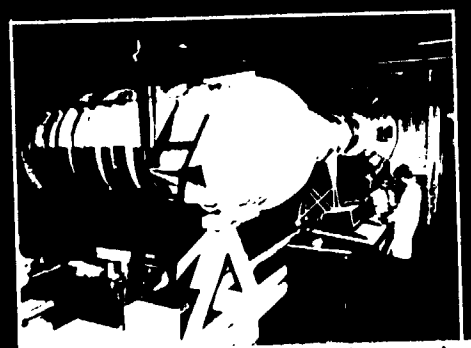
6x19in.
Transonic Tunnel

0.3m Transonic
Cryogenic Tunnel



6x18in.
Smoke Tunnel

13x11in.
MSBS Tunnel

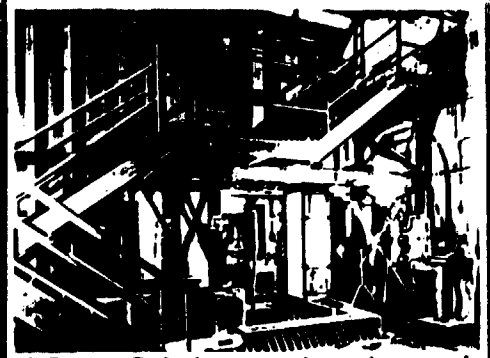


18x18in. Basic Aerodynamics
Research Facility (BARF)

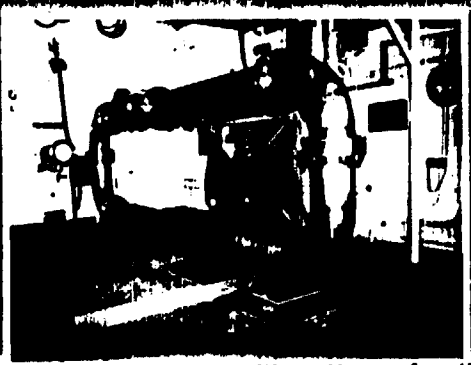
SMALL RESEARCH FACILITIES

Transonic Aerodynamics Division

Jet exit static test stand

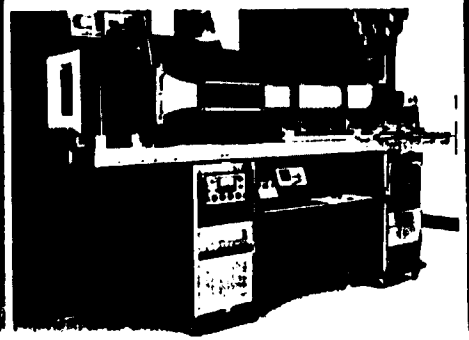


16 x 24 in. water tunnel



6 cm hot-wire calibration facility

4 x 10 in. diagnostic tunnel

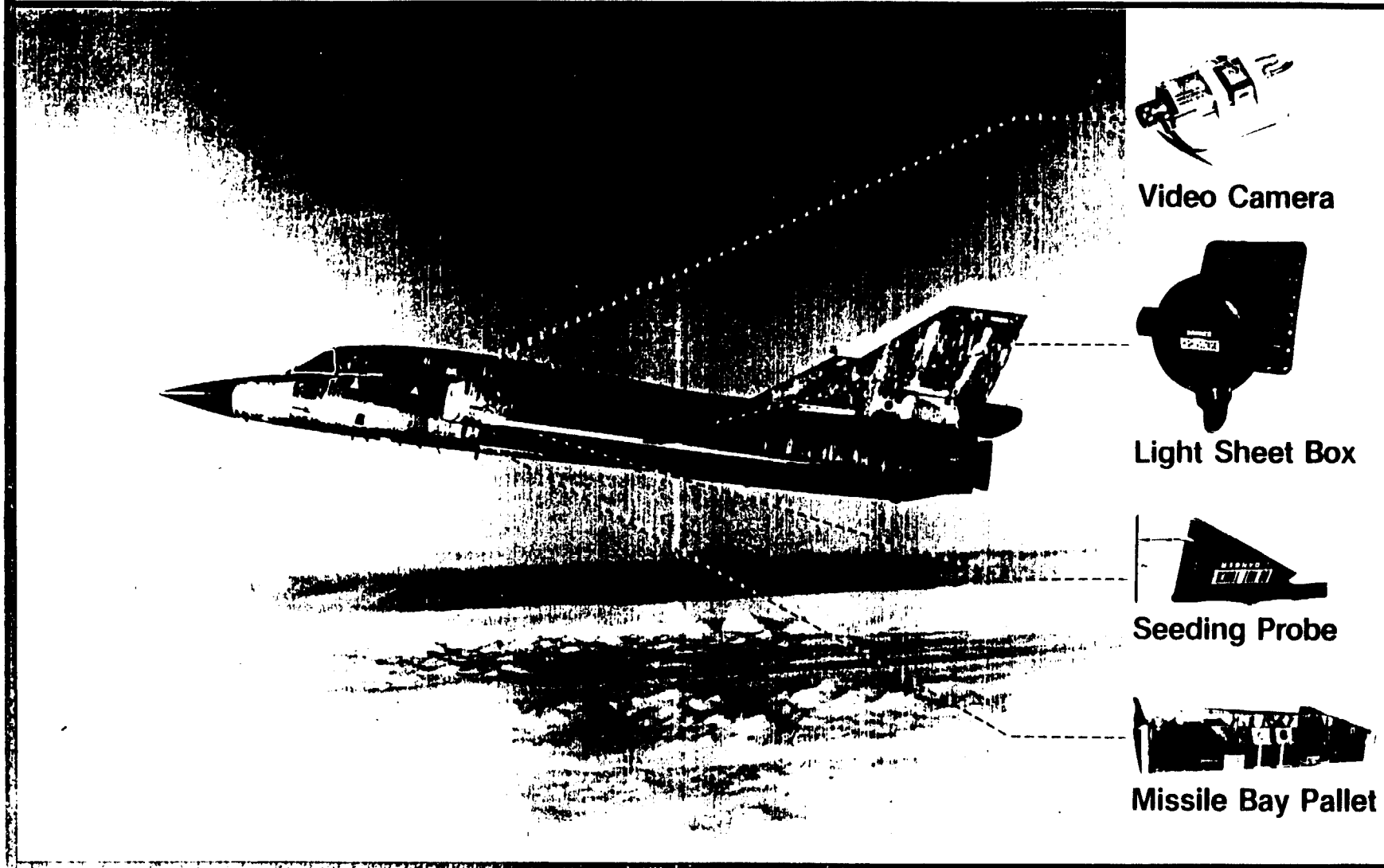


2 x 5.5 in. diagnostic tunnel

INSTRUMENTATION DEVELOPMENTS

- FLIGHT AND WIND TUNNEL FLOW VIS
- 3-COMPONENT LDV
- THIN FILM ARRAYS
  - TRANSITION
  - SEPARATION AND REATTACHMENT
  - HOT AND COLD ENVIRONMENTS
- 3-WIRE HOT WIRE FOR TRANSONIC MEASUREMENTS
- LASER TRANSITION DETECTION

F-106 FLOW VISUALIZATION ELEMENTS



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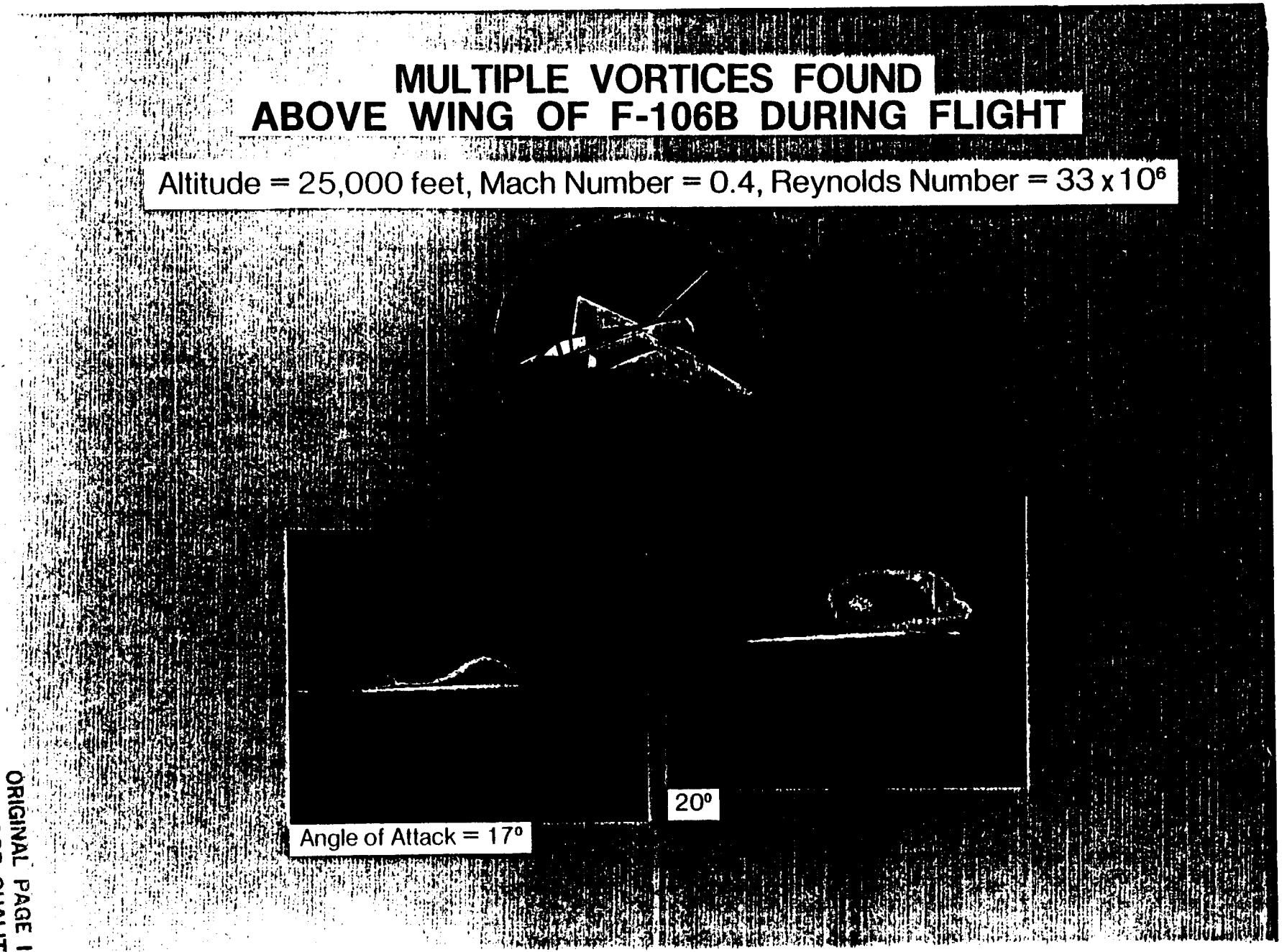
L-87-126



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L-87-2294

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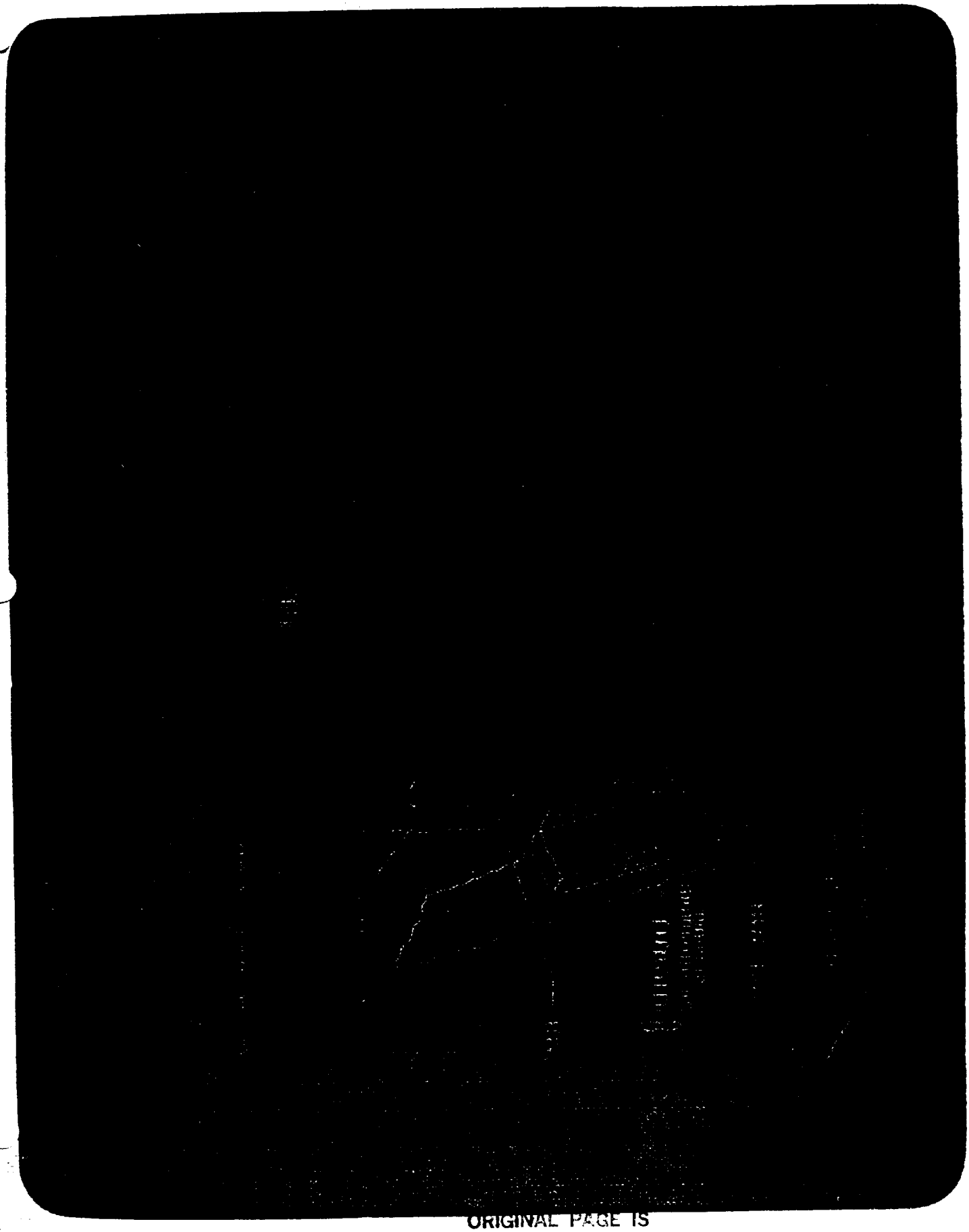

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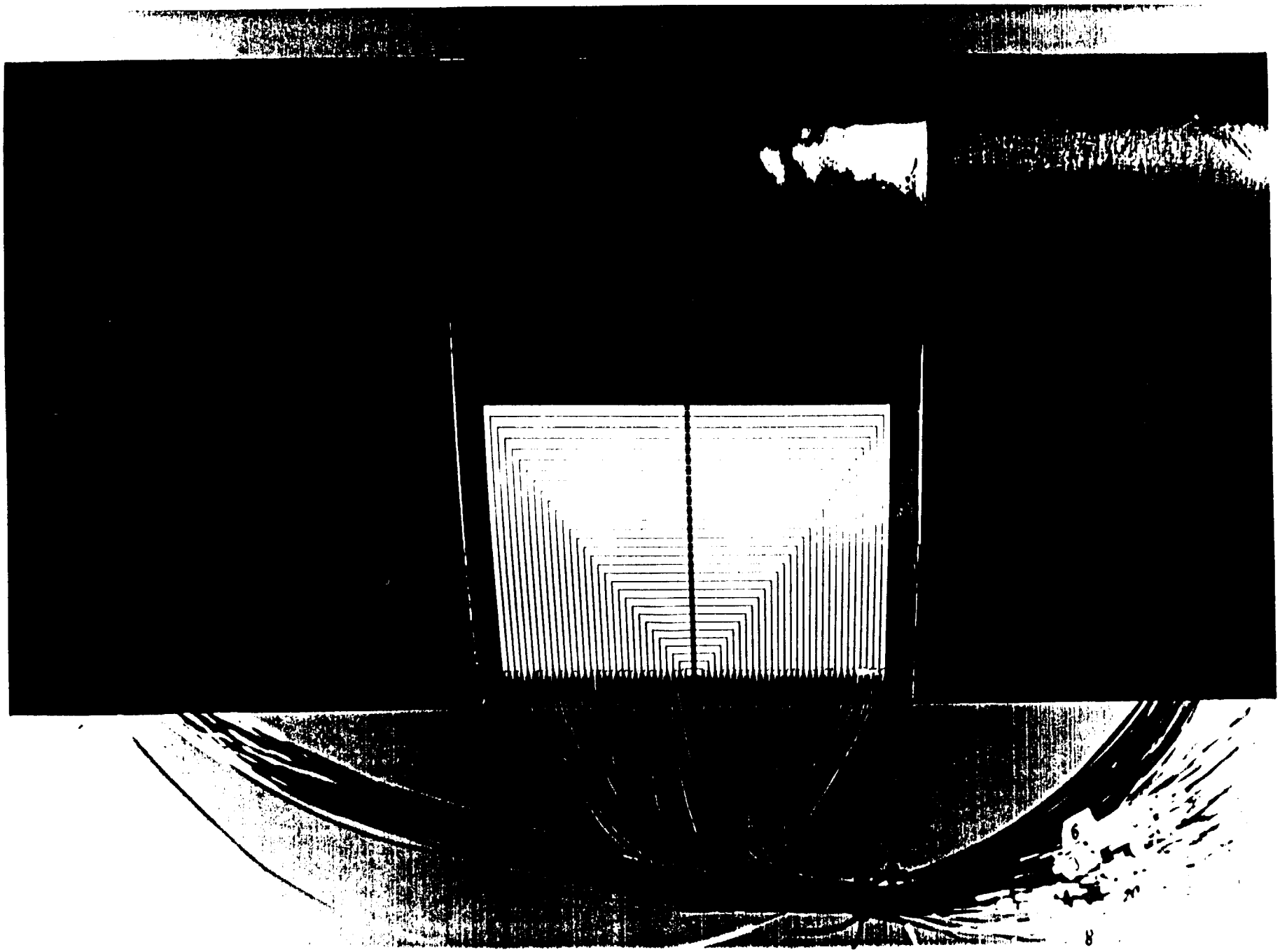
Hampton, Virginia 23665-5225



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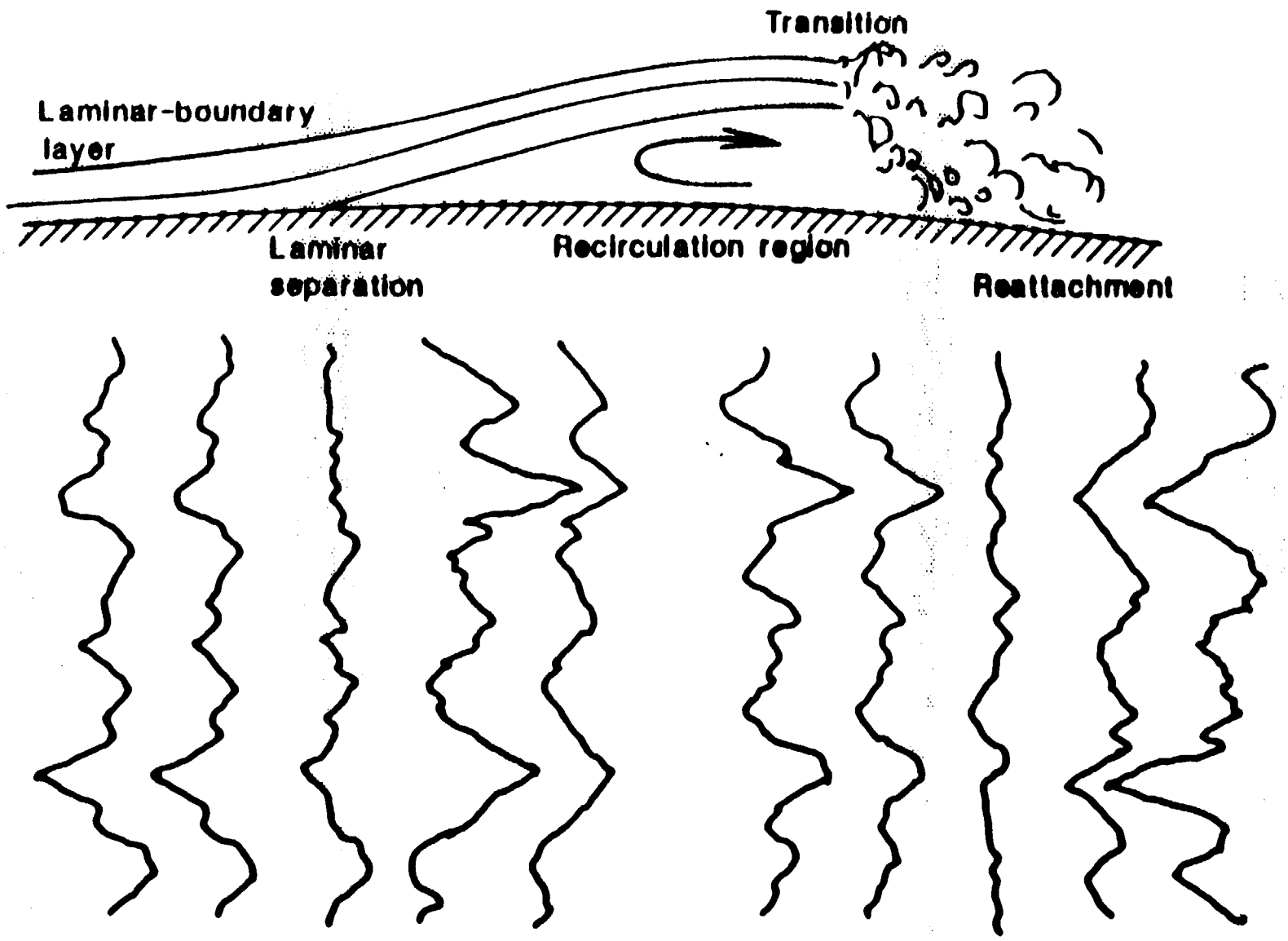
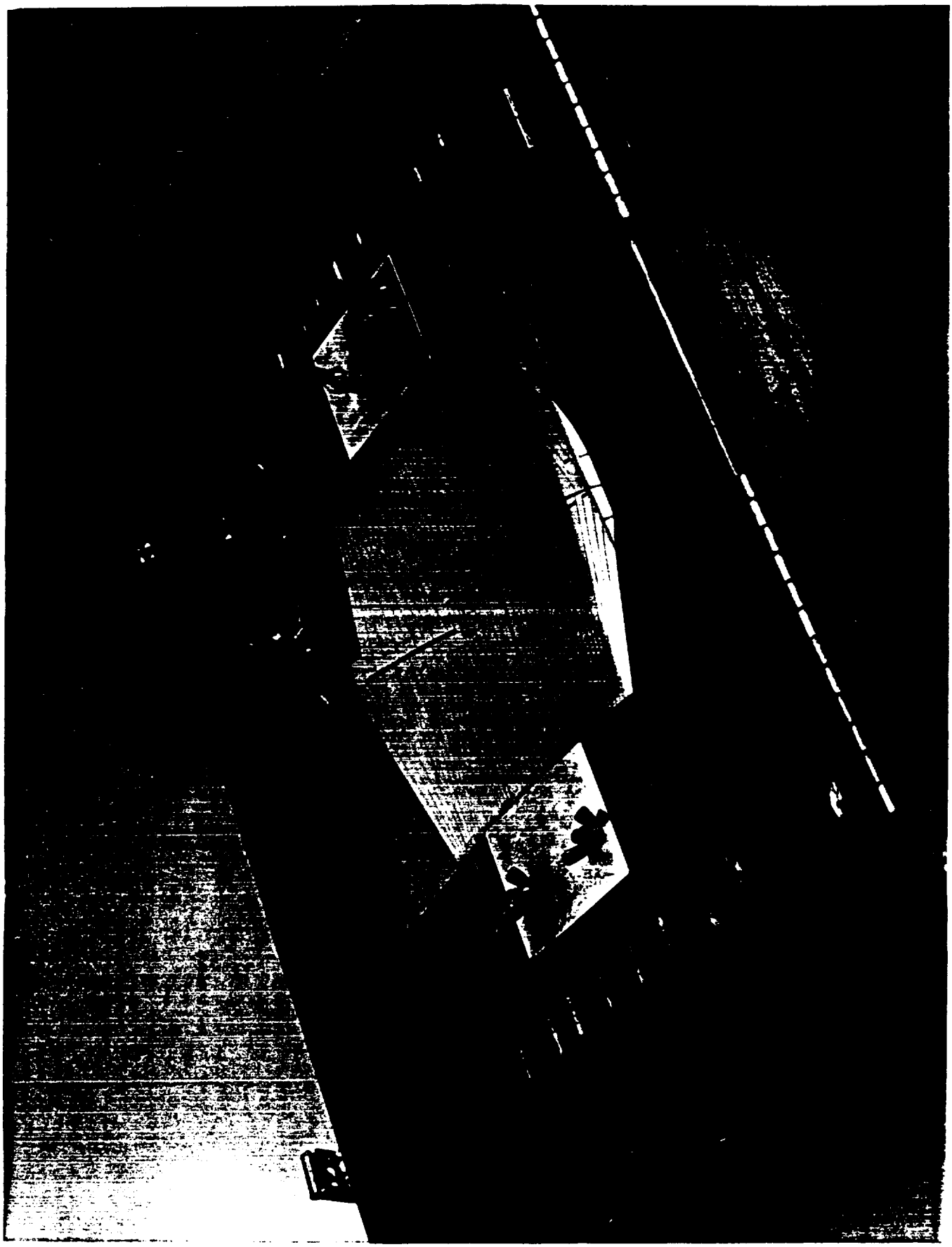
MULTI-ELEMENT THIN FILM DIAGNOSTICS





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Space Administration

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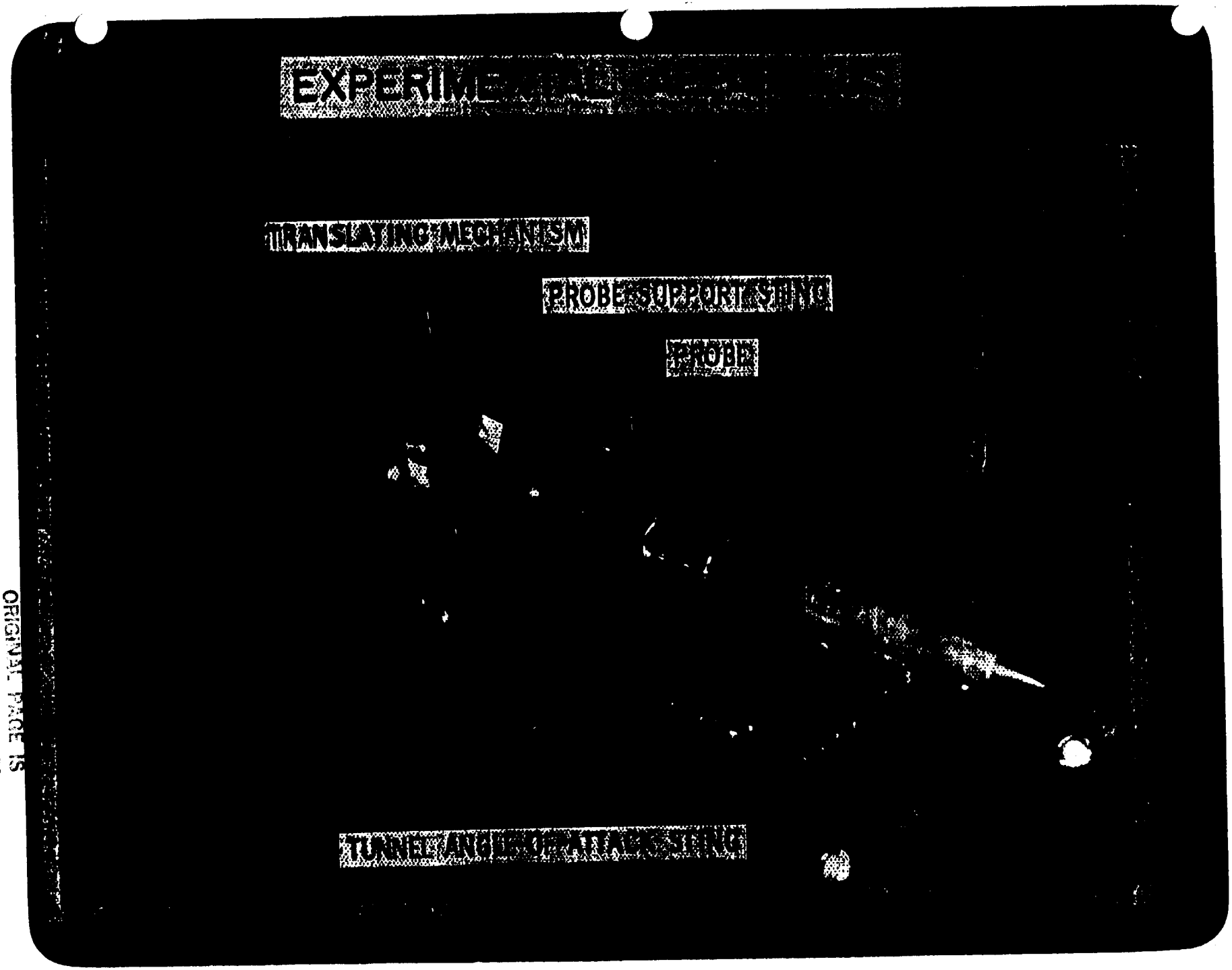

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AREAS OF RESEARCH

- TRANSITION W/WO CONTROL
- SEPARATION W/WO CONTROL
- JUNCTURE FLOWS
- VORTEX FLOWS INCLUDING VORTEX CONTROL - ALSO ORIGINATION, GROWTH, BREAKDOWN, INTERACTIONS
- INLET ENVIRONMENTS
- AFTERBODY/EXHAUST FLOW FIELDS
- NOZZLE CONCEPTS
- NACELLE/PYLON/WING INTERACTION
- PROP WAKE/WING/FUSELAGE INTERACTION
- AIRFOIL AND WING-DESIGN
- CONFIGURATION AERODYNAMICS
- HIGH RN BOUNDARY LAYERS
- INDUCED DRAG
- STORE INTEGRATION
- INSTRUMENT ACCURACY
- WALL INTERFERENCE

N/O NACP

CODE VALIDATION RESEARCH PROJECTS

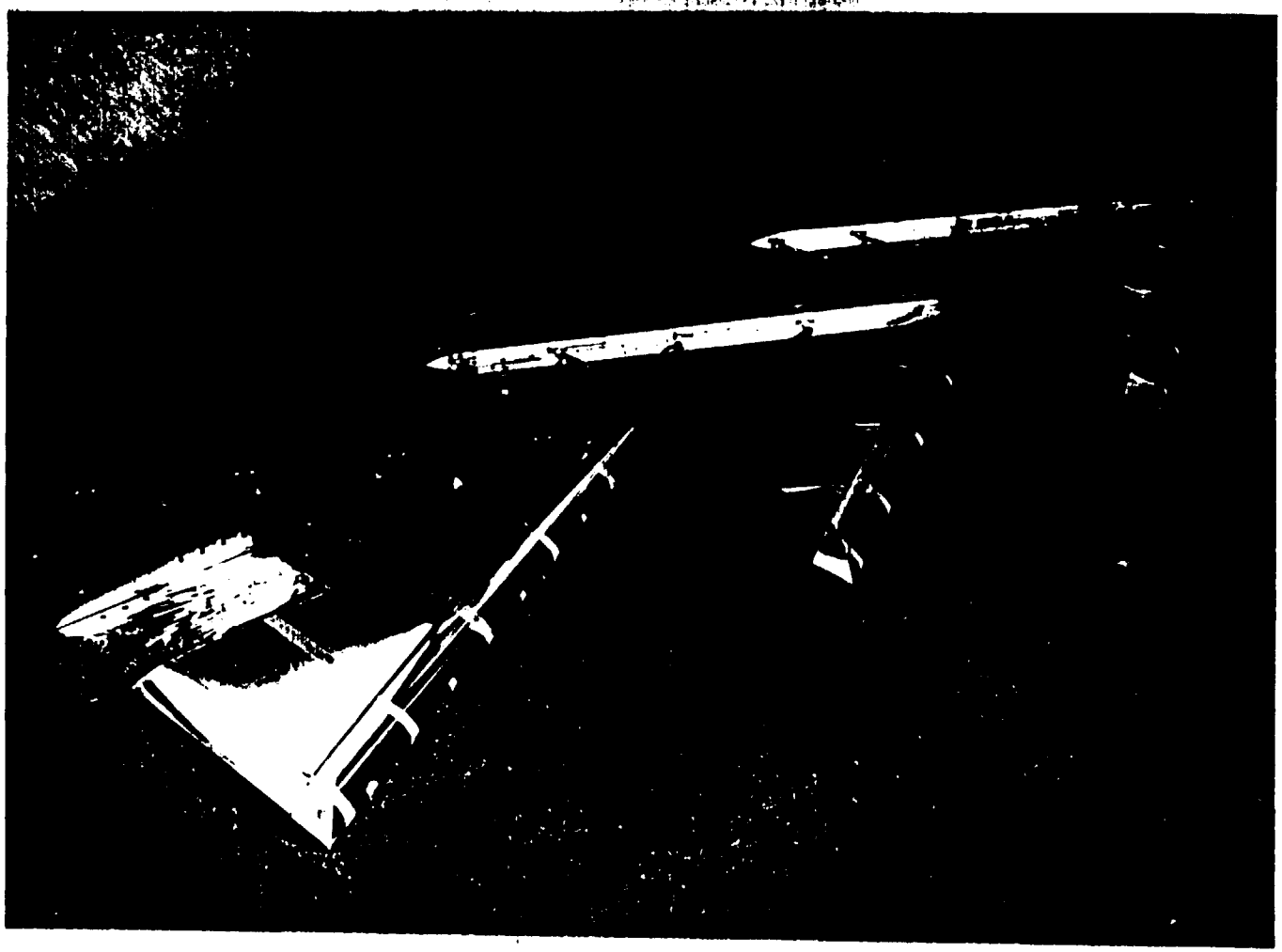
- VORTEX FLOWS -

- 65° DELTA FLOW FIELD
- McDONNELL DOUGLAS FIGHTER-WING FLOW FIELD
- BOEING SUPERCRUISER MODEL - 350 FLOW FIELD
- F-106 FLIGHT AND WIND TUNNEL EXPERIMENTS
- 5° CONE
- MISSILE FOREBODY

EXPERIMENTAL 65 DEGREE DELTA-WING CONCEPT

- Purpose: Develop generic data base to guide theory development
  - Attached and separation-induced vortex flows
  - Mach numbers up to 1.2
  - Chord Reynolds numbers up to 200 million
  - Independent Mach and Reynolds number control
- Capture salient flow features
  - Sharp and blunt leading-edge separation
  - Secondary vortex separation and transition
  - Vortex breakdown
- Simple geometry
  - Isolated delta wing
  - Fully analytic surfaces, continuous through 2nd derivative
  - Representative of "full-scale" conditions

65 DEGREE NTF DELTA WING



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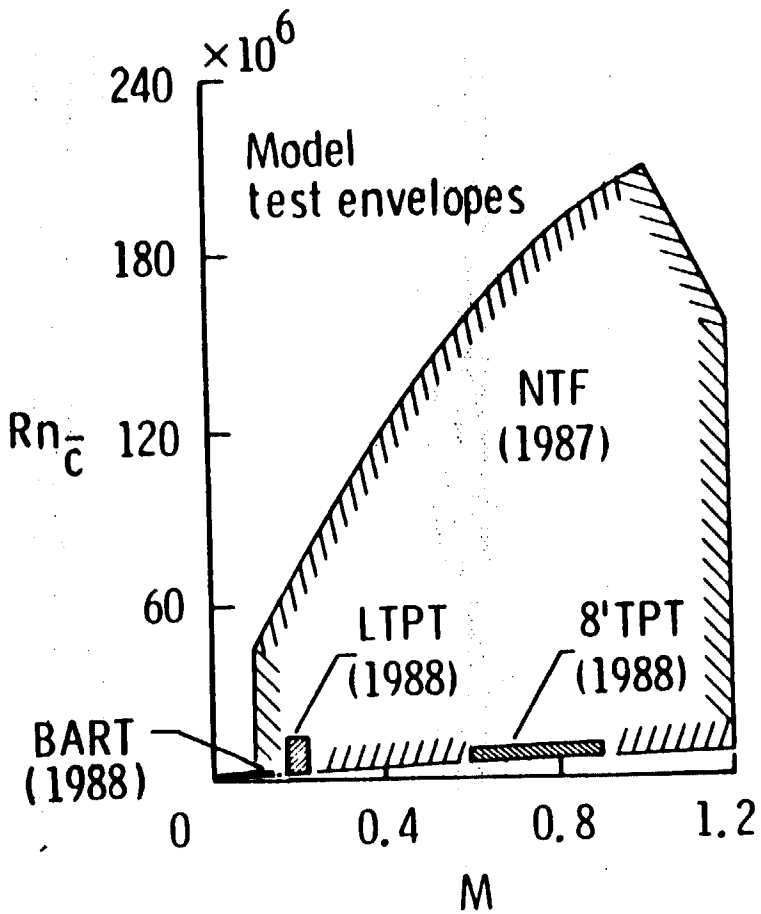
65° DELTA WING EXPERIMENTAL PROGRAM

$0 \leqslant \alpha \leqslant 30°$

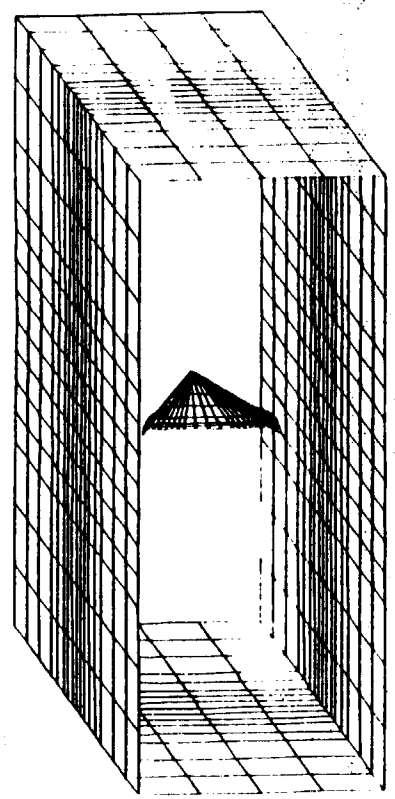


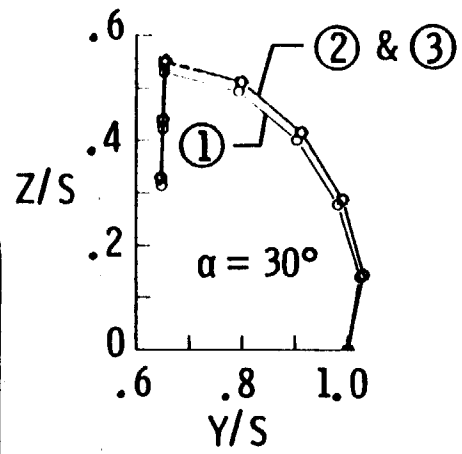
Planned Testing

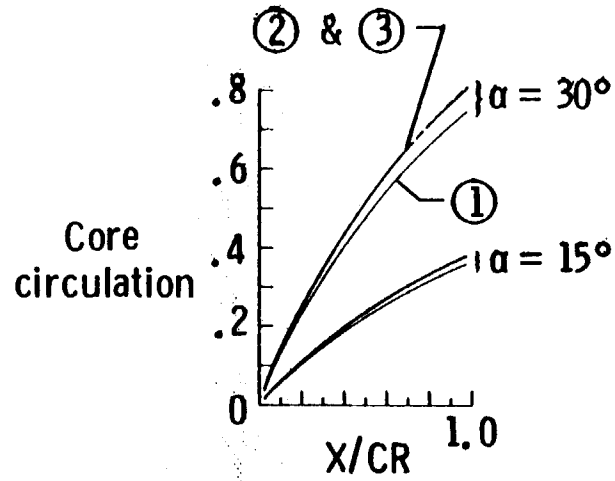
- National Transonic Facility
  - Static surface pressures
  - Root bending moment
  - Buffet
  - Vortex core condensation
- Low turbulence pressure tunnel
  - Static surface pressures
  - LDV (2-D)
  - Flow visualization
- 8-foot transonic pressure tunnel
  - Static surface pressures
  - LDV (3-D)
  - Flow visualization
- Basic Aerodynamic Research Tunnel
  - Static surface pressures
  - LDV (3-D)
  - Total pressures in flow field
  - Flow visualization

FVS STUDY OF WALL EFFECTS ON OFFBODY FLOW AROUND 65° DELTA WING

$M = 0.22$, $X/C_R = 0.5$, Model/tunnel span = 0.5







FVS wing model

① Free air (F.A.)

② With LTPT walls

③ F.A. with Δα correction

LEFT

BOEING SUPERCRUISER MODEL 330
IN LRC 16 FOOT TRANSONIC TUNNEL

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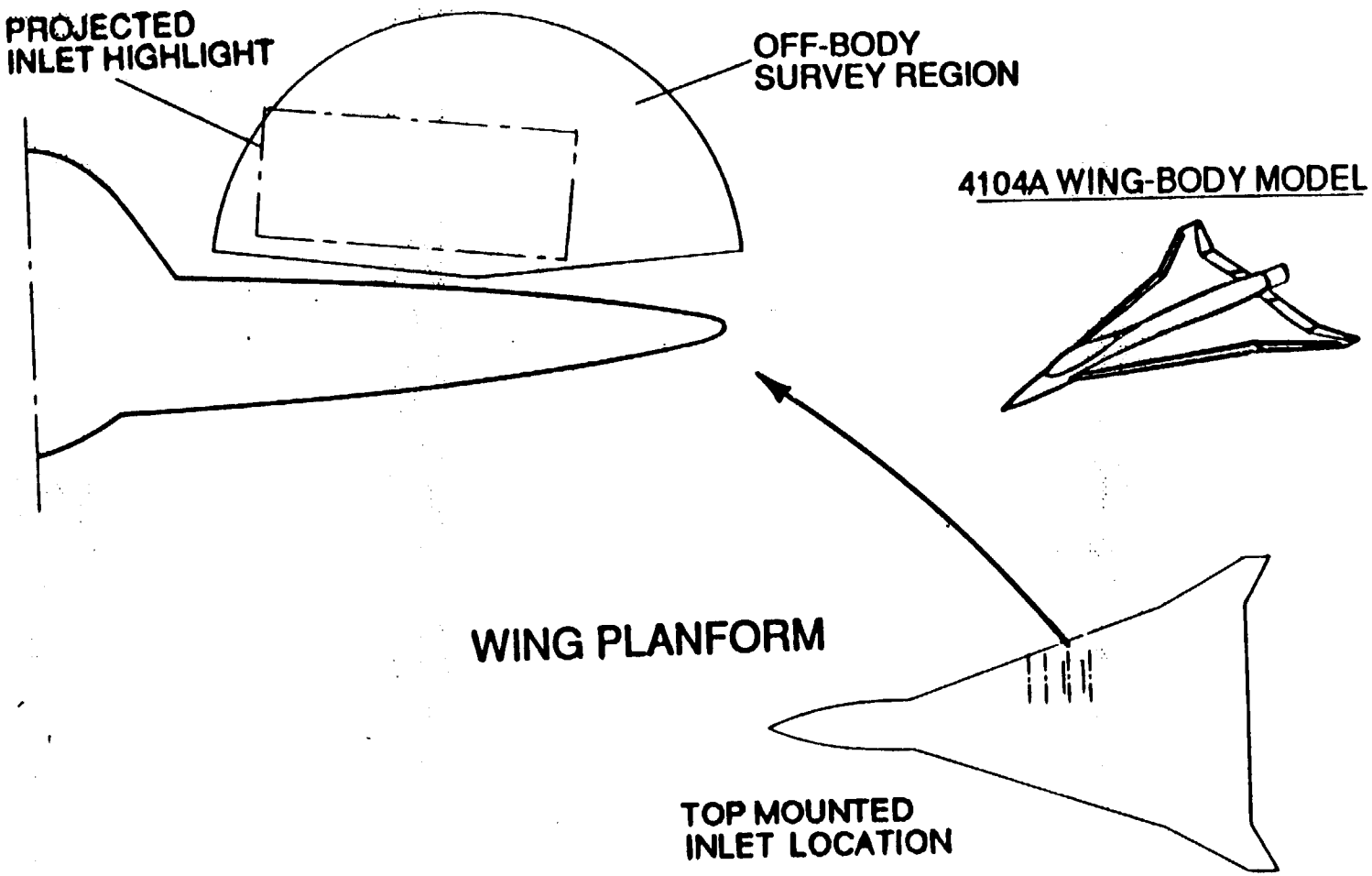
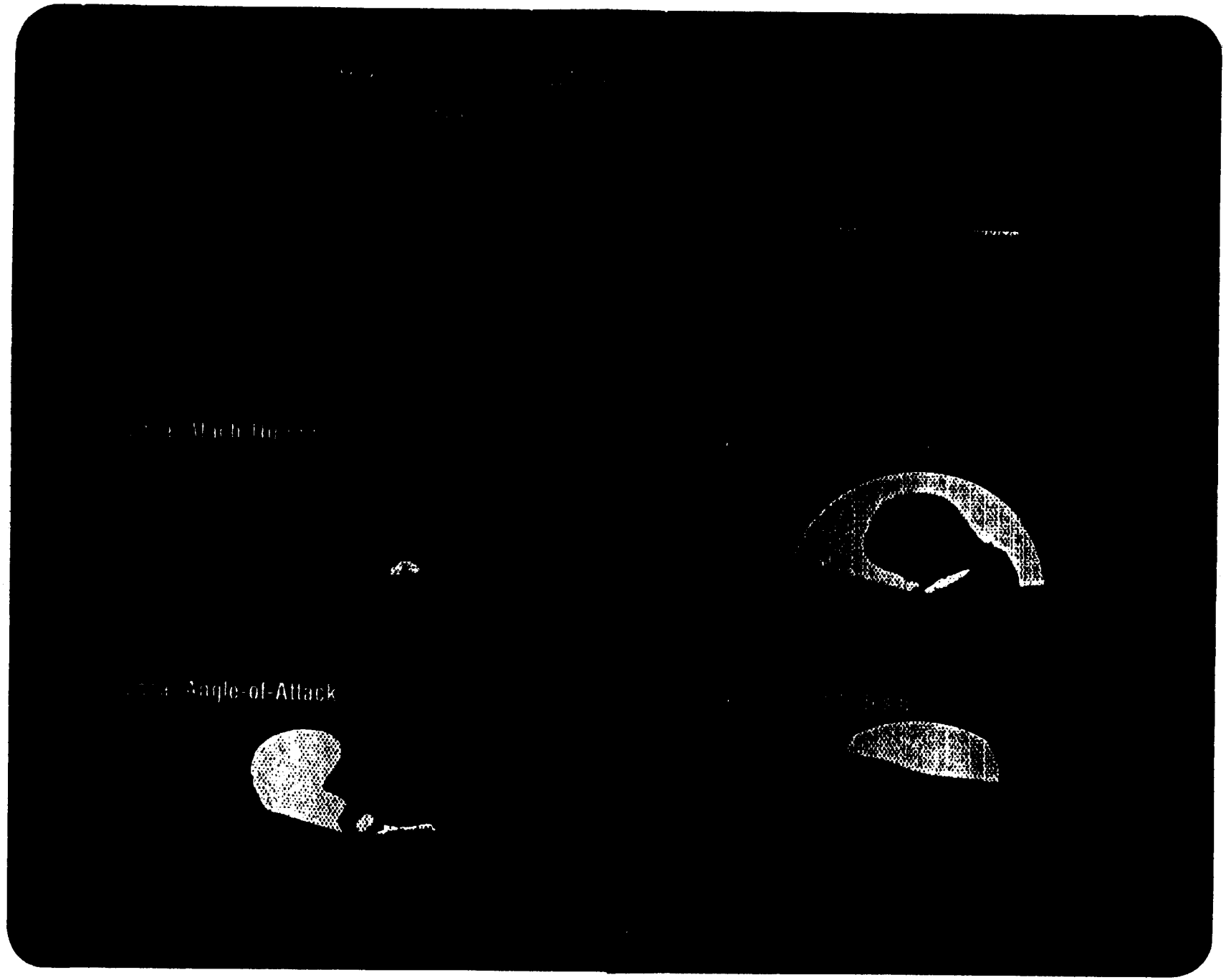
FUSELAGE SURVEY STATIONS OVER-THE-WING SURVEYS



MCDONNELL AIRCRAFT COMPANY



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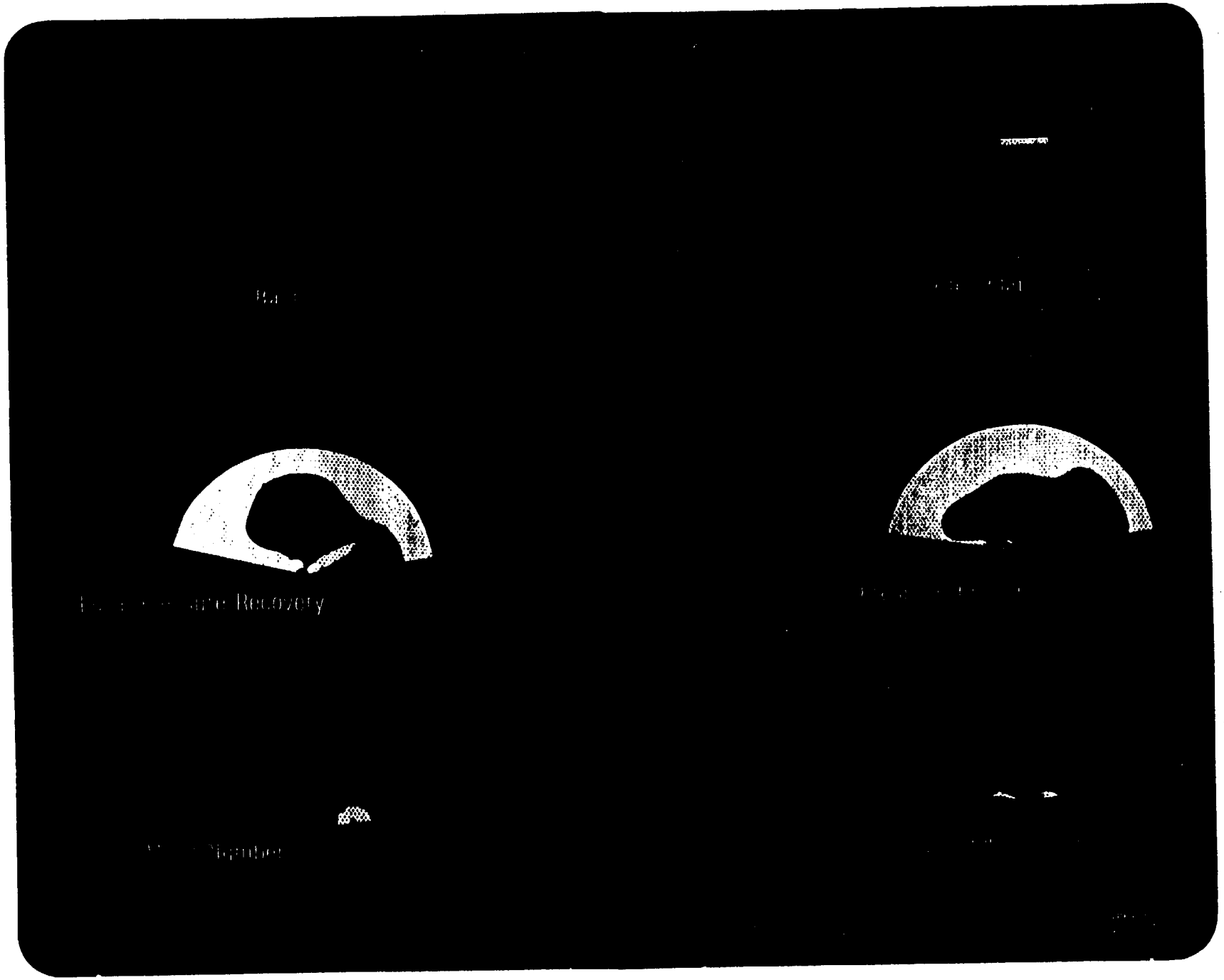

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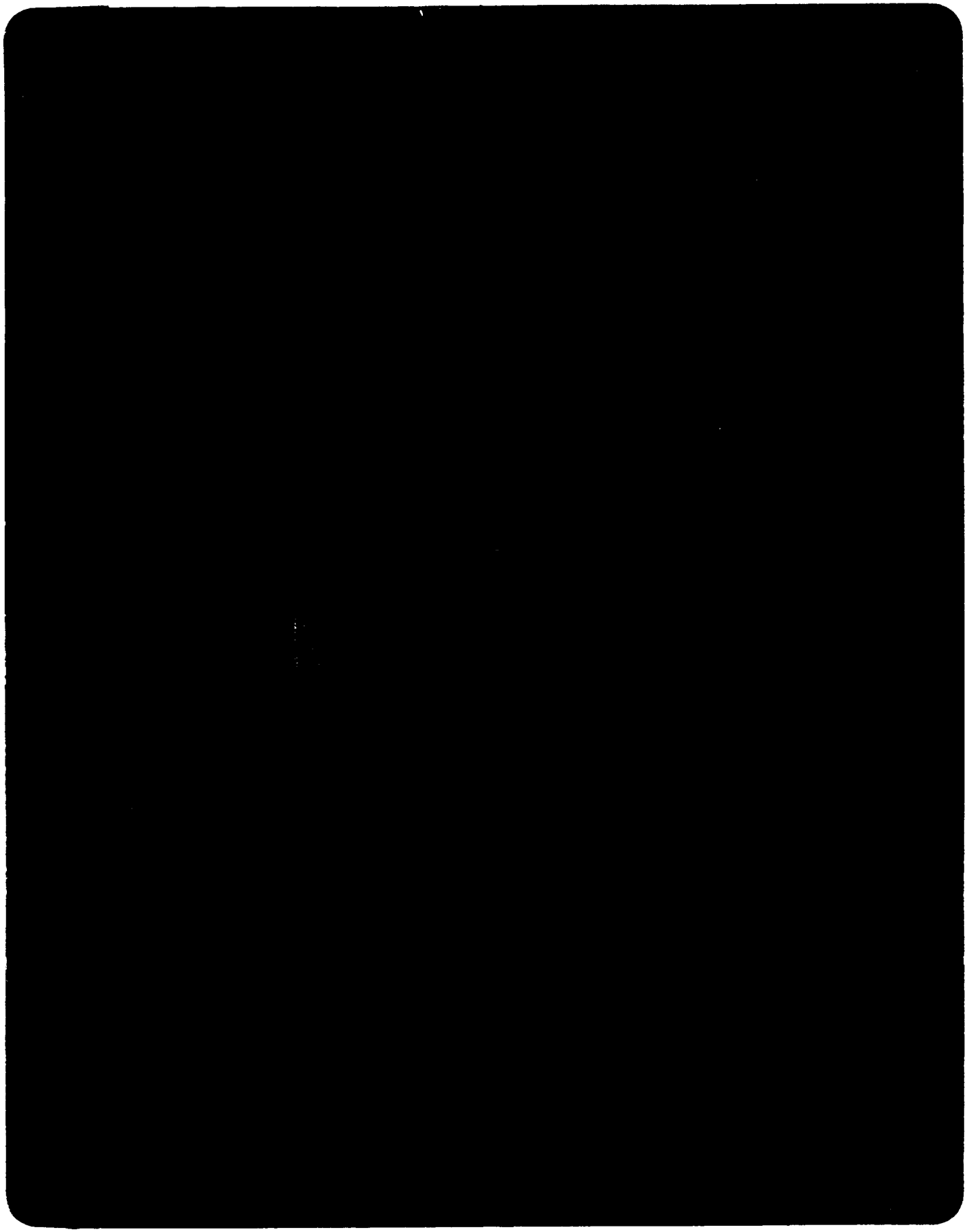
CODE VALIDATION RESEARCH PROJECTS

- PROPULSION INTEGRATION -

- PRESSURES ON INSIDE AND OUTSIDE OF NACELLES
  - LAMINAR AND TURBULENT DESIGNS
- GENERIC TURBOFAN PYLON/NACELLE/WING INTERFERENCE - PRESSURE MEASUREMENTS
- PRESSURES ON AFTERBODIES FOR A VARIETY OF ENGINE/NOZZLE ARRANGEMENTS
- FLOW FIELD AROUND AXISYMMETRIC NOZZLE
- PRESSURES IN FLOW FIELD BEHIND RECTANGULAR NOZZLE
- PRESSURES INSIDE NONAXISYMMETRIC NOZZLES W/WO THRUST REVERSERS
- STRAIGHT AND SWEPT WING PRESSURES BEHIND TURBOPROP
- FLOW FIELD SURVEYS IN REGIONS WHERE INLETS MIGHT BE LOCATED



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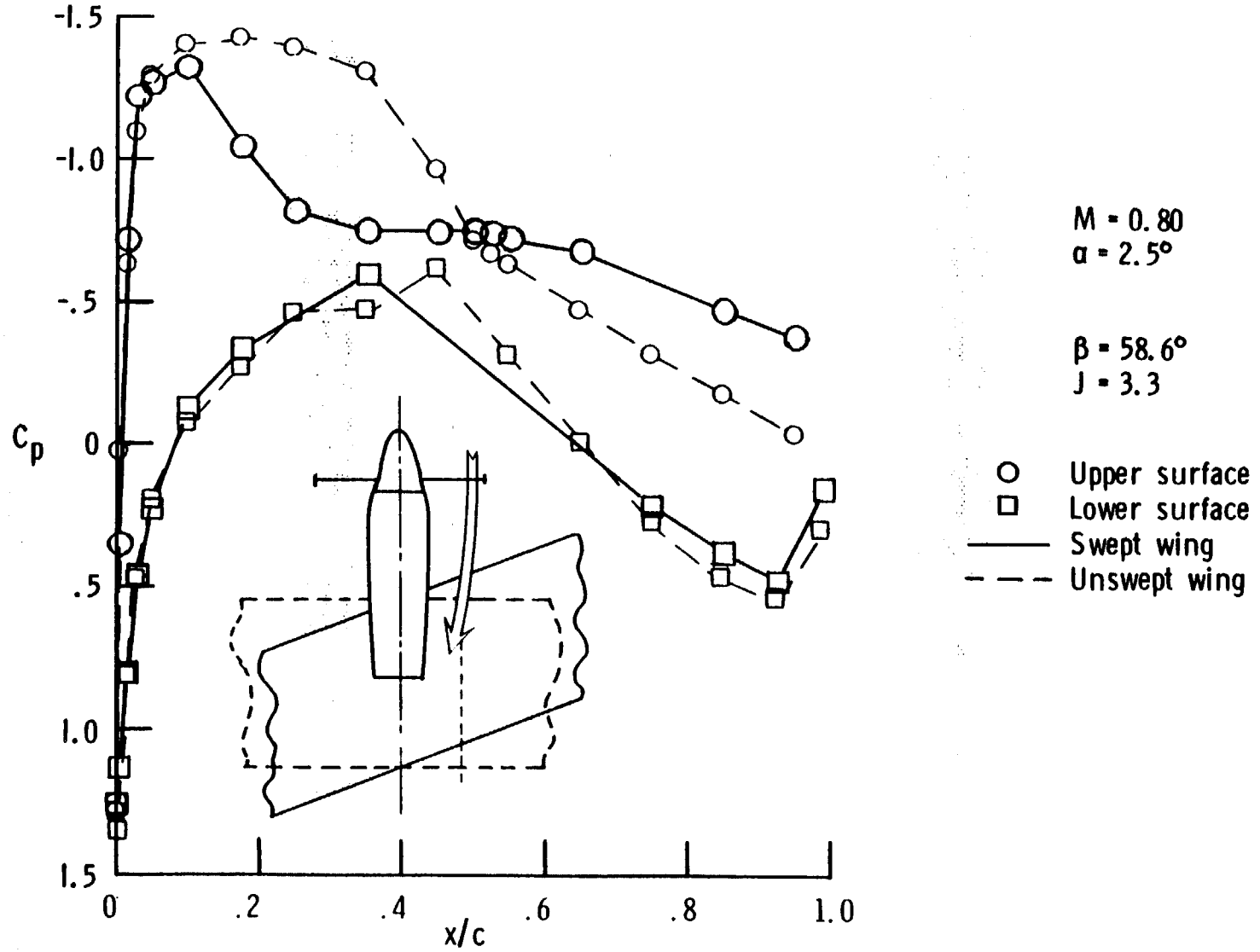
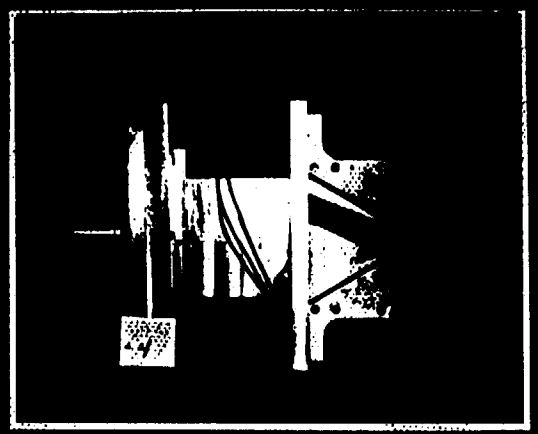
EFFECT OF WING SWEEP WITH COUNTER-CLOCKWISE PROPELLER ROTATION ON THE INBOARD WING PANEL

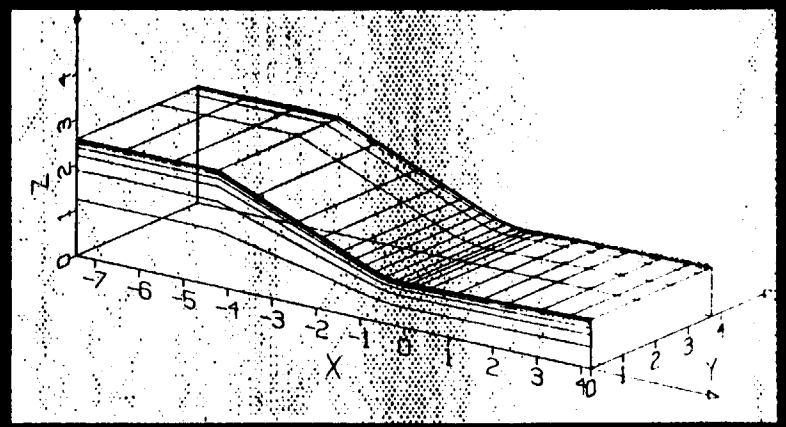


3-D NAVIER STOKES PREDICTIONS

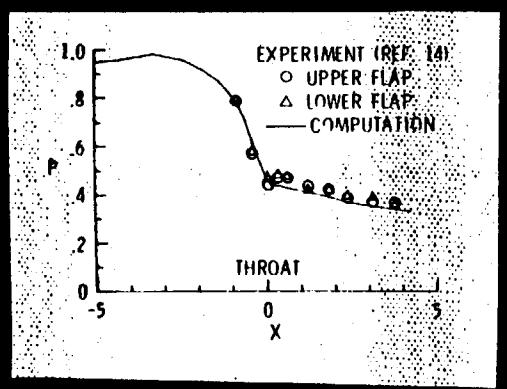
MODEL



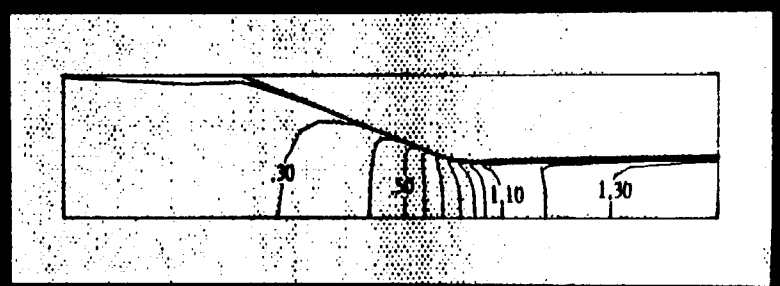
COMPUTATIONAL GRID



SURFACE PRESSURES IN CENTER PLANE



MACH NUMBER CONTOURS IN CENTER PLANE



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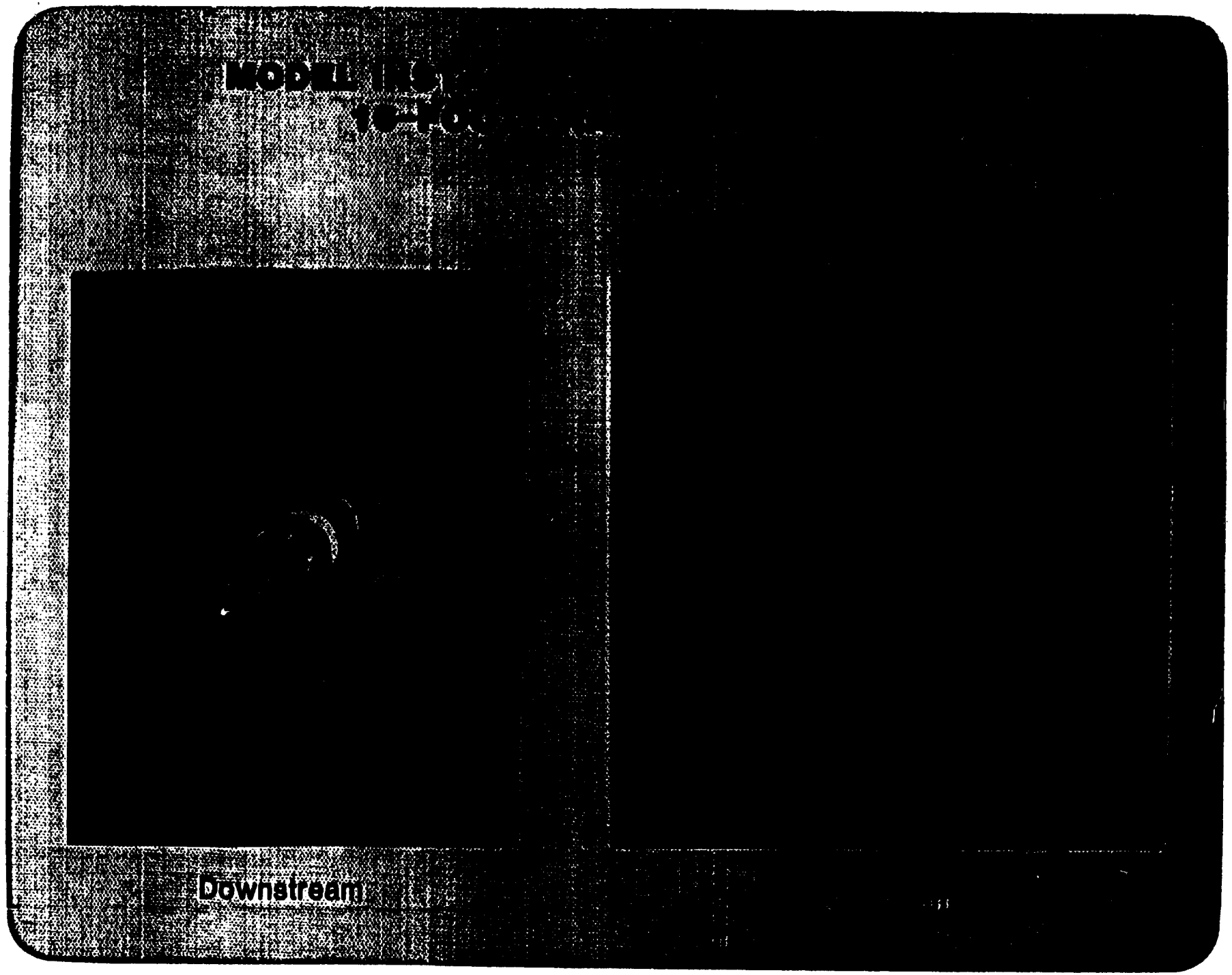

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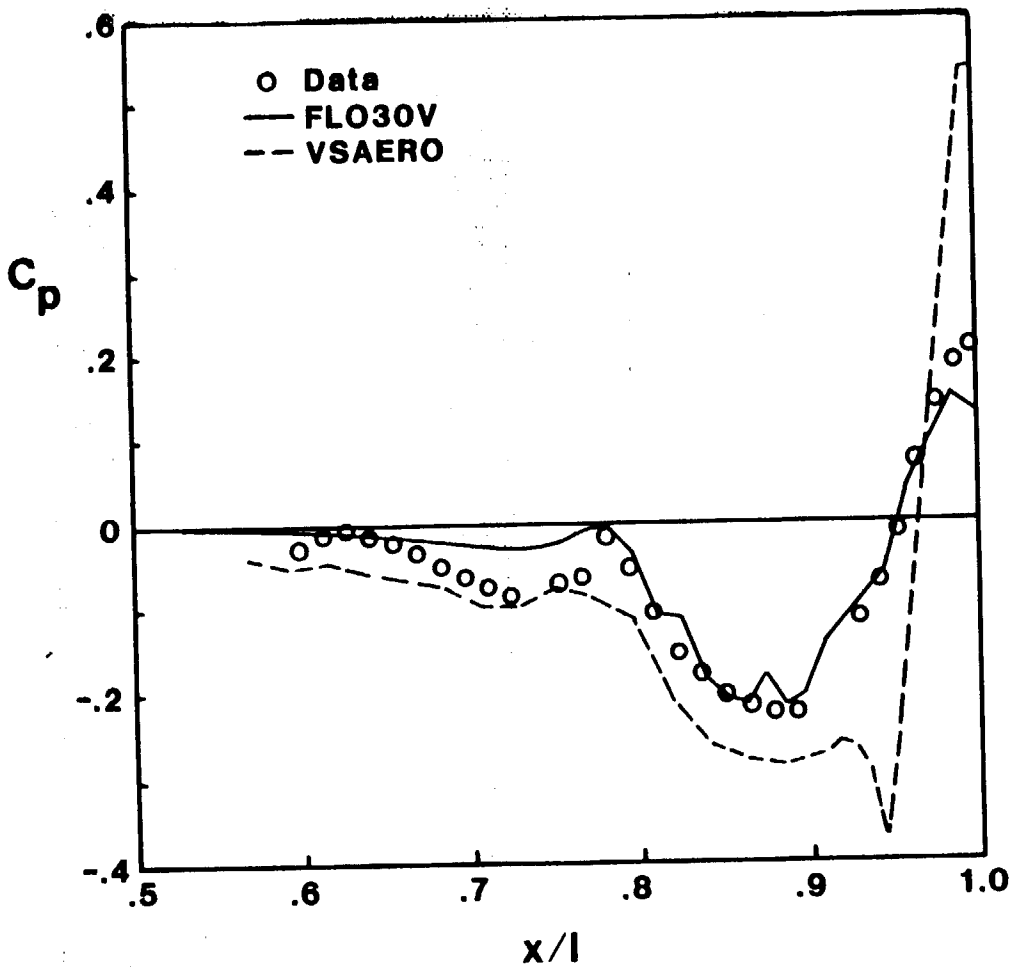
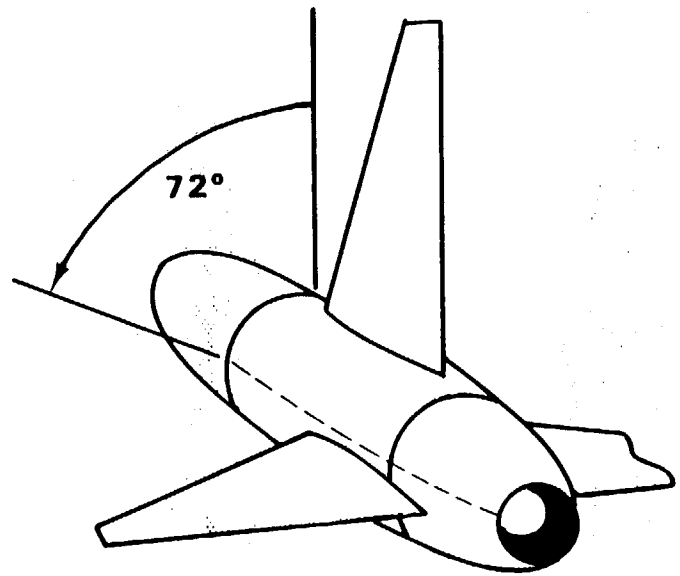
EXPERIMENTAL AND NUMERICAL RESULTS FOR THE STAGGERED TAIL ARRANGEMENT

(M = 0.9, NPR ≈ 5.0)





CODE VALIDATION RESEARCH PROJECTS

- FIGHTERS -

- PATHFINDER II
- F-18
- F-111 TACT
- X-29
- McDONNELL DOUGLAS ADVANCED WING
- GRUMMAN ADVANCED WING
- GENERAL DYNAMICS WING

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L-87-2438

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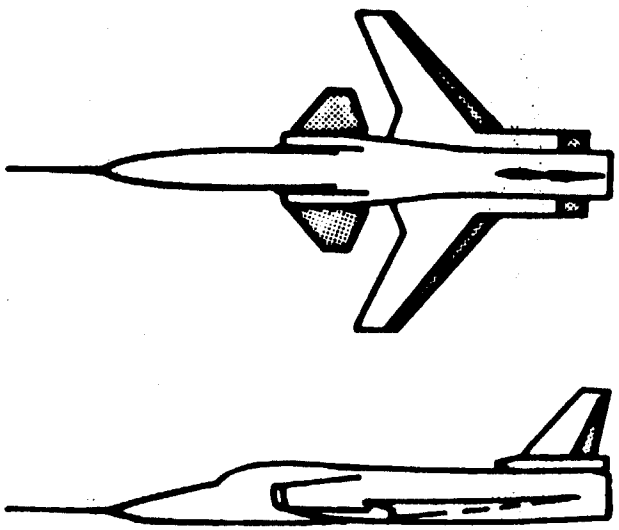
X-29A ADVANCED TECHNOLOGY DEMONSTRATOR FLIGHT / WIND TUNNEL / COMPUTATIONS



- OBJECTIVES
  - WIND TUNNEL TO FLIGHT CORRELATION
  - REYNOLDS NUMBER EFFECTS
    - Performance
    - Static Stability
    - Wing Pressure Distributions
    - High Angle-of-Attack
  - CODE "CALIBRATION"
    - Small-Disturbance
      - TRO-3D
      - Batina Aeroelastic
    - Full-Potential
      - TAWFIVE
      - Steinhoff
    - TLNS
      - TAB-1
      - CFL-3D

NO 33 R

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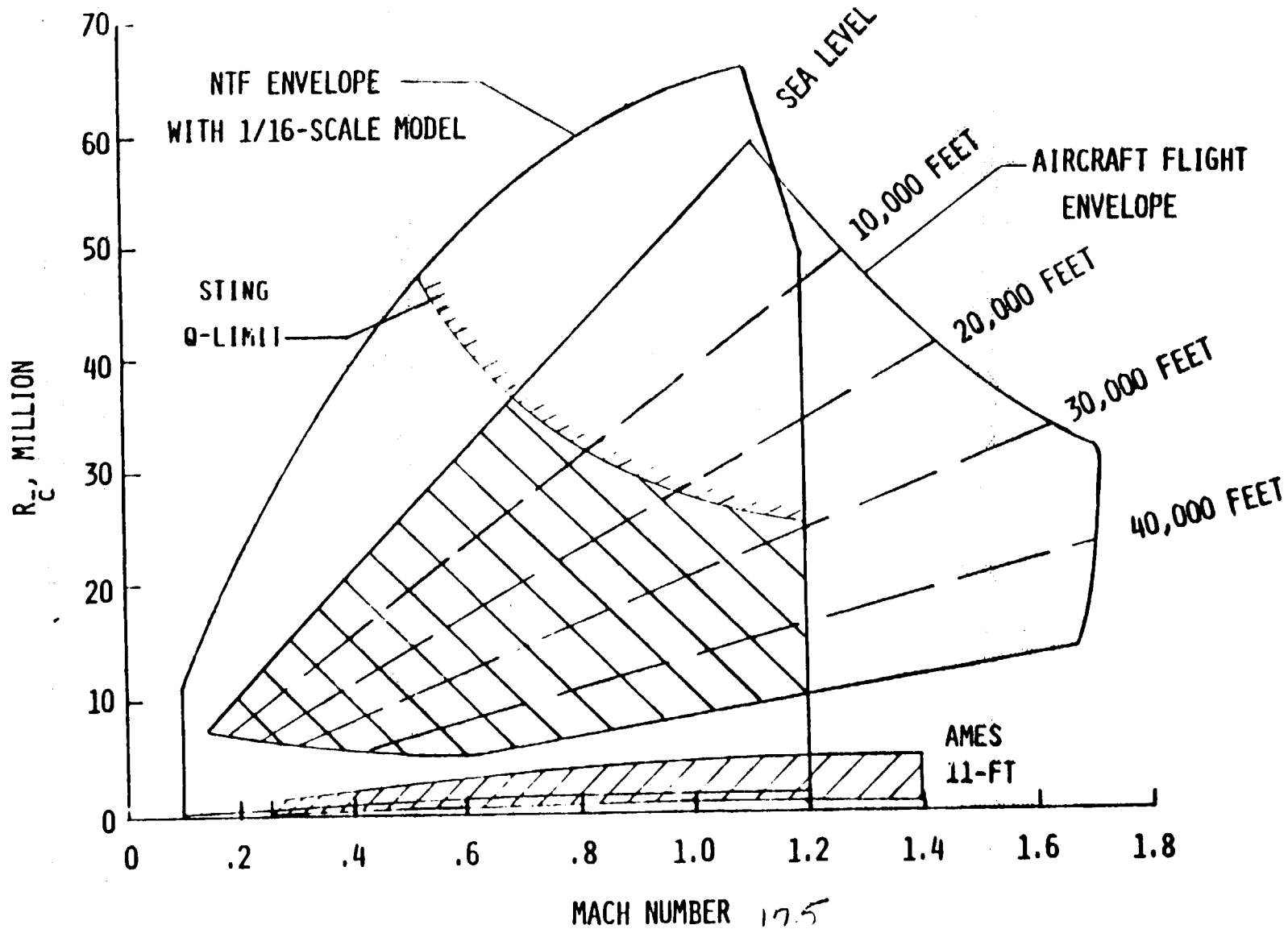
COMPARISON OF NTF AND X-29A FLIGHT ENVELOPES

1/16-SCALE X-29



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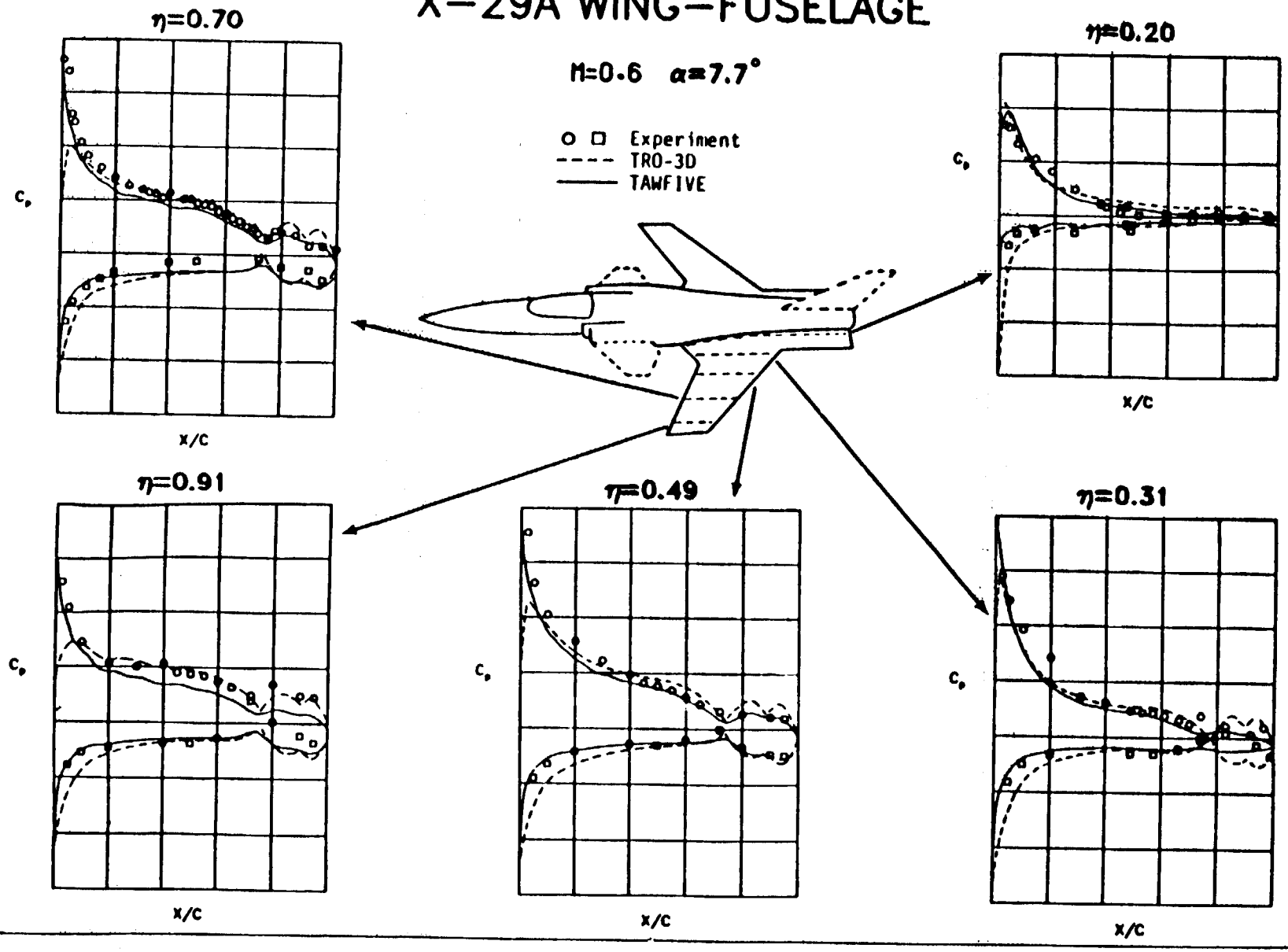
COMPARISON OF WIND TUNNEL DATA AND COMPUTATIONAL RESULTS

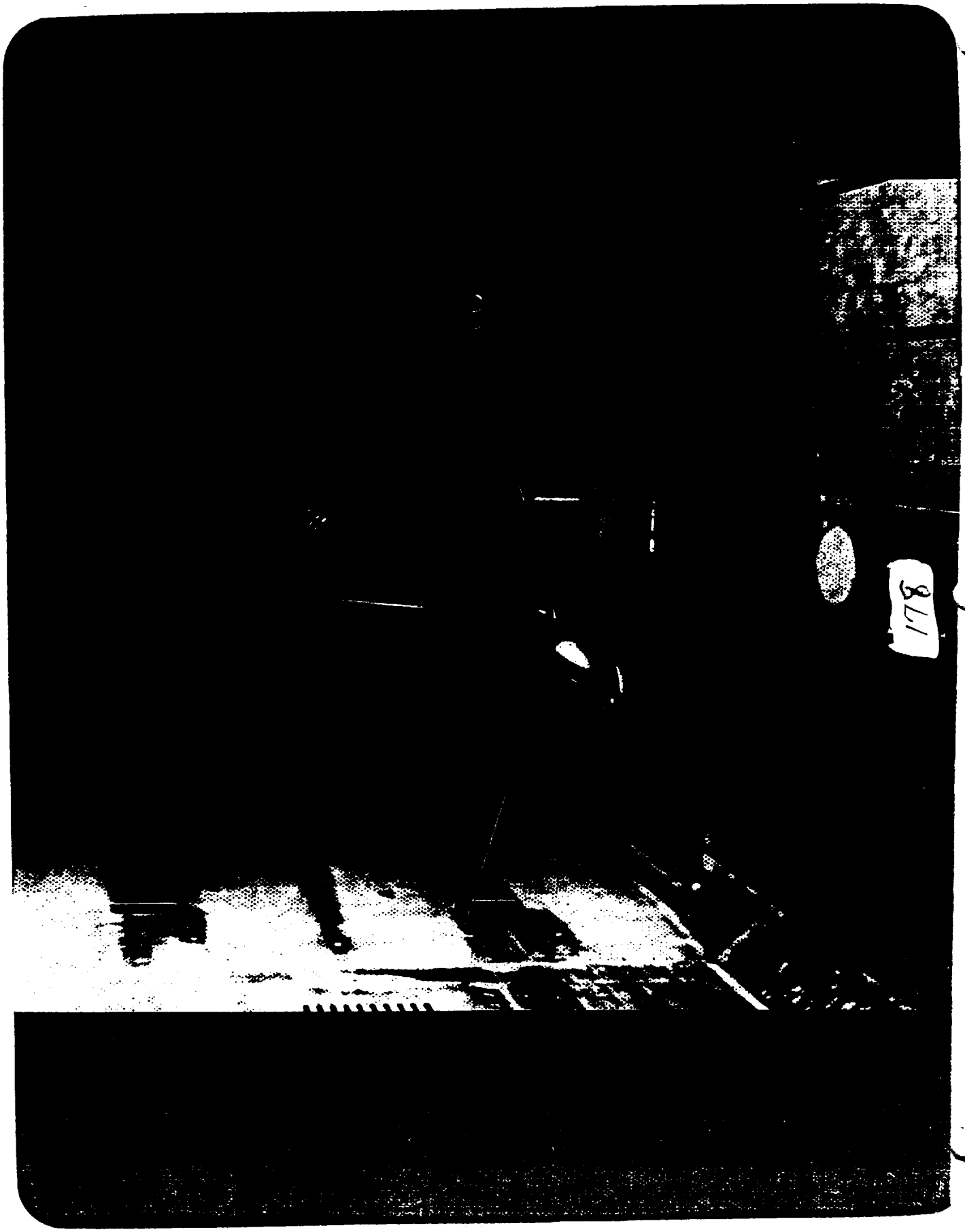
X–29A WING–FUSELAGE



CODE VALIDATION RESEARCH PROJECTS

- TRANSPORTS -

- HIGH-WING TRANSPORT - DOUGLAS AIRCRAFT COMPANY
- HIGH-WING/PATHFINDER I FUSELAGE - LOCKHEED GEORGIA
- LOW WING/PATHFINDER I FUSELAGE - LOCKHEED CALIFORNIA
- LOW WING/PATHFINDER FUSELAGE - DOUGLAS AIRCRAFT COMPANY
- B-767
- PATHFINDER I



National Aeronautics and
Space Administration

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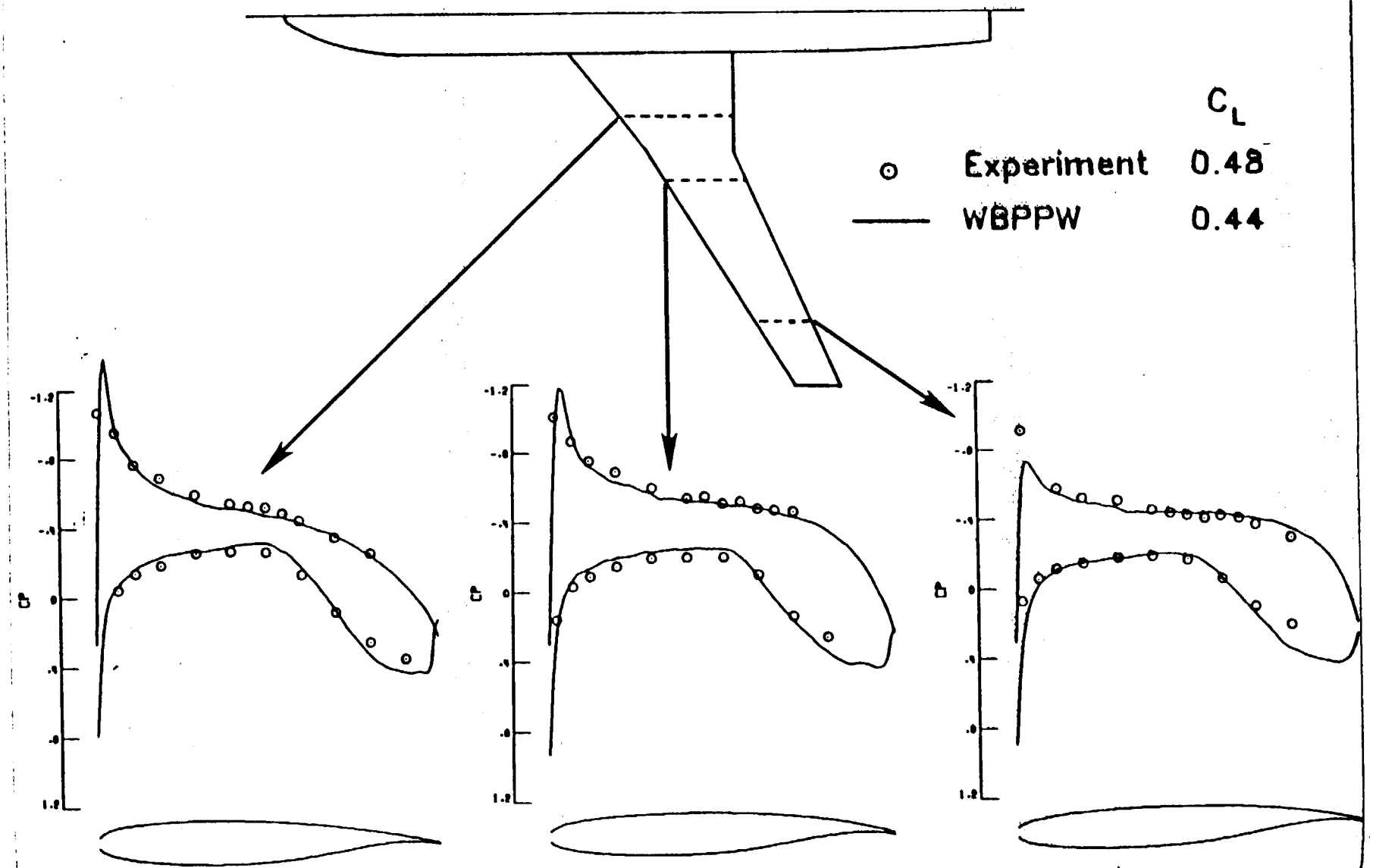
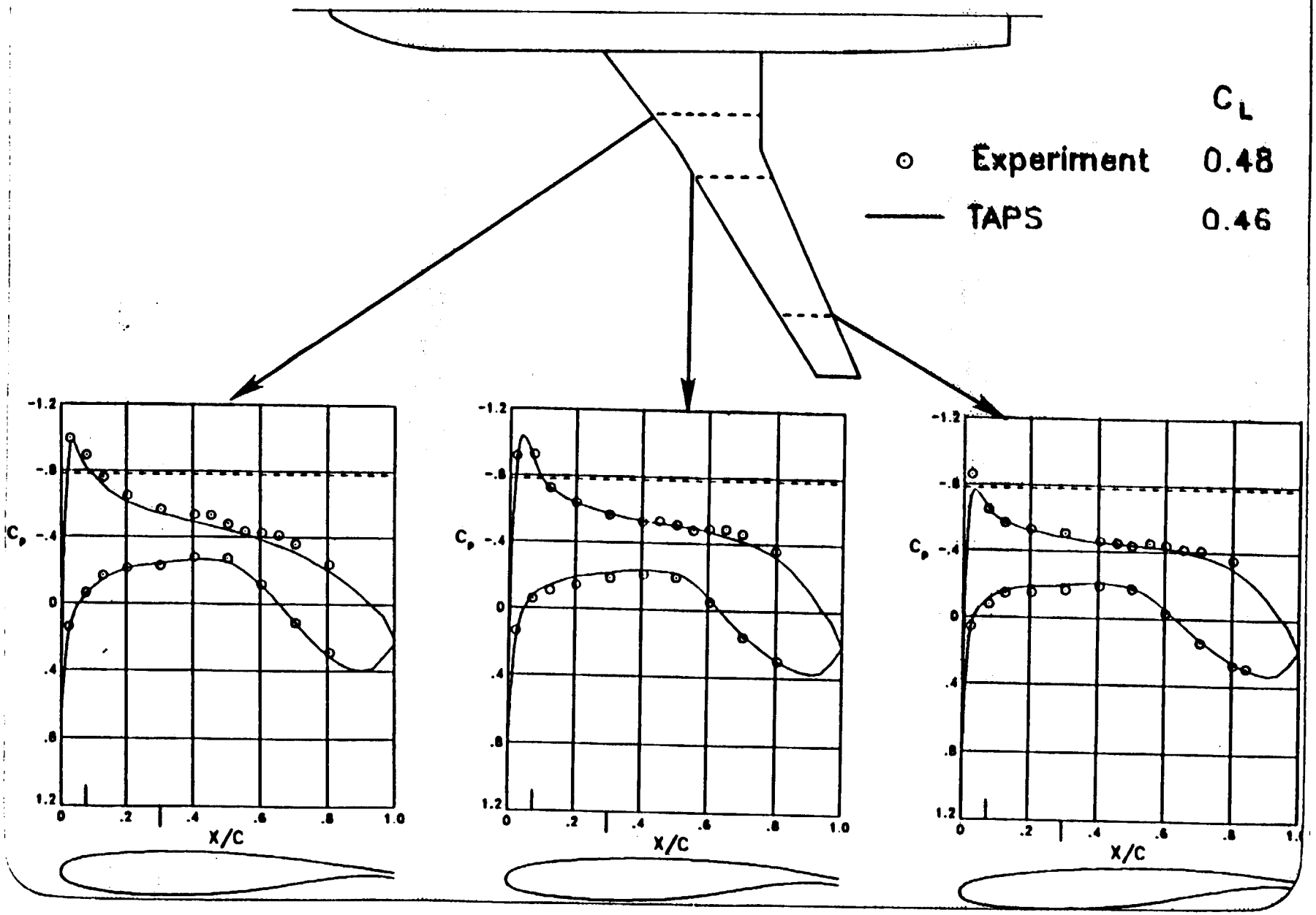
PATHFINDER I

$M = 0.70 \quad \alpha = 2.0^\circ \quad R_N = 5.3 \times 10^6$



PATHFINDER I

$M = 0.70 \quad \alpha = 2.0^\circ \quad R_N = 5.3 \times 10^6$

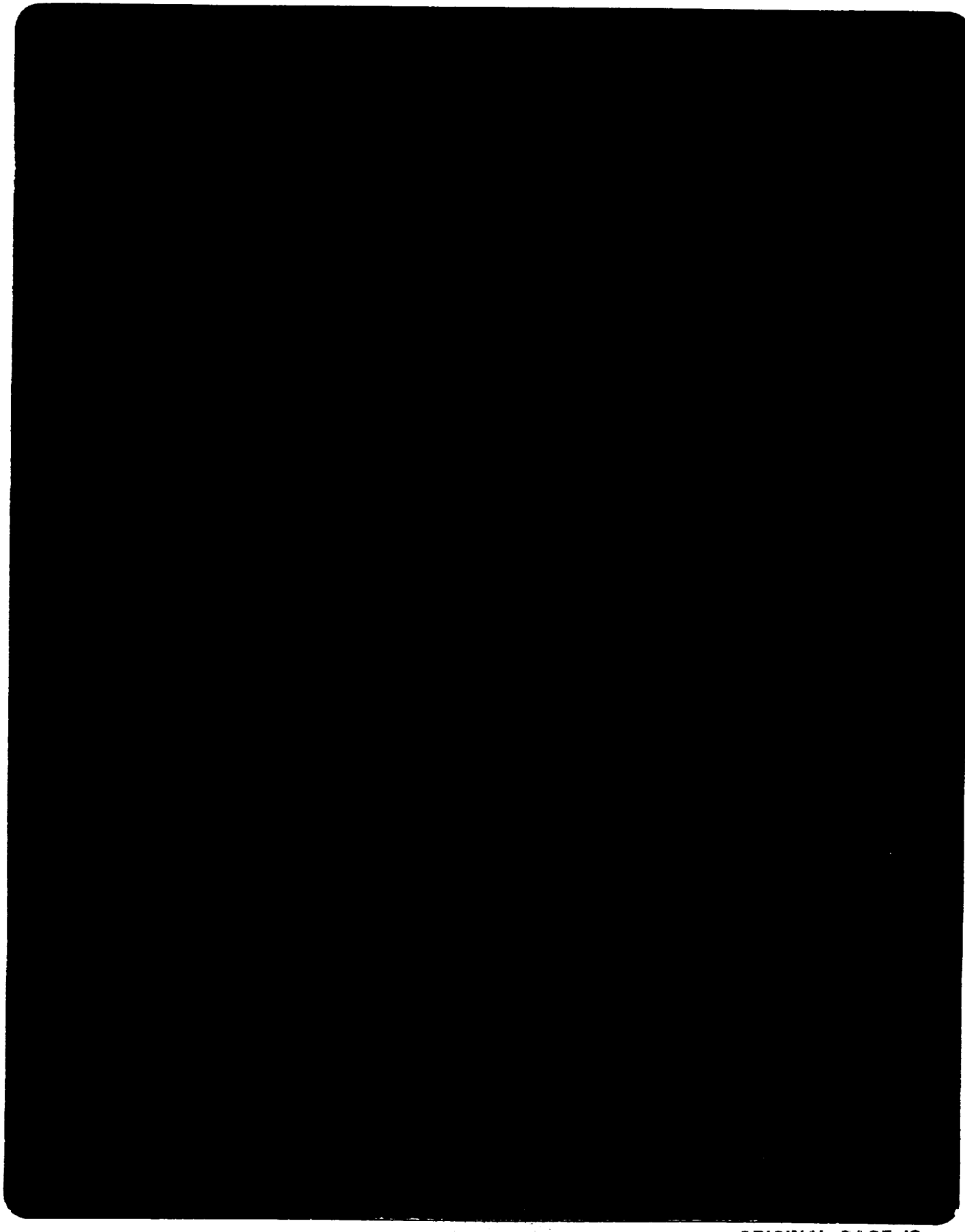


CODE VALIDATION RESEARCH PROJECTS

- BOUNDARY LAYER STABILITY THEORY -

- 8-FOOT TPT LAMINAR FLOW CONTROL (LFC) EXPERIMENT
- 8-FOOT TPT HYBRID LFC EXPERIMENT
- NLF AIRFOILS
  - GENERAL AVIATION
    - NLF(1)-0414
    - NLF(2)-0415
    - EPPLER 387
  - COMMUTER AND EXECUTIVE
    - NLF(1)-0213
  - RPV
    - NLF(1)-1015
    - LRN(2)-1010
- F-14 VARIABLE SWEEP TRANSITION FLIGHT EXPERIMENT (VSTFE)
- YAWED WING - UNIVERSITY OF ARIZONA AND LANGLEY
- TAYLOR GOERTLER LTPT EXPERIMENT

TOP



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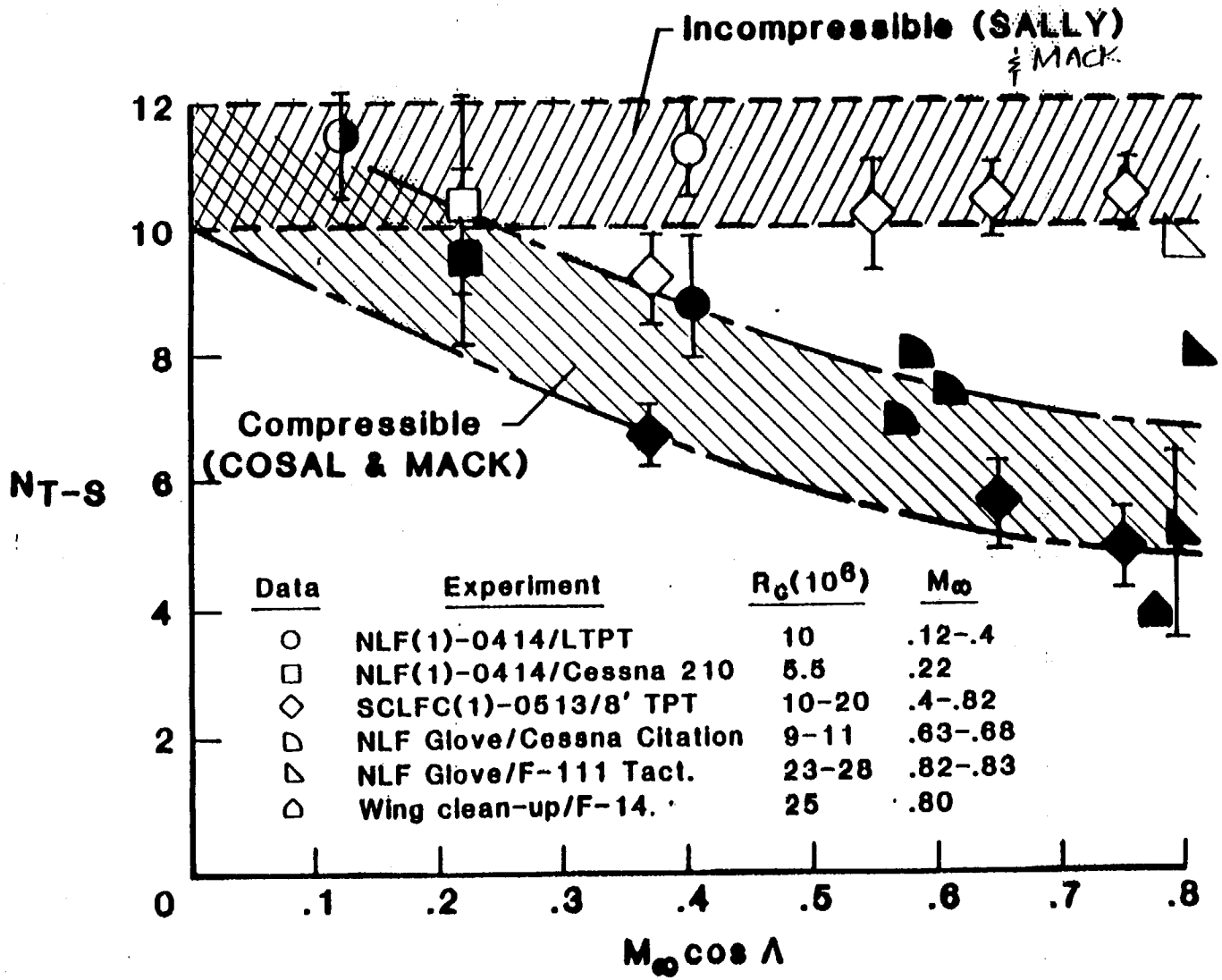
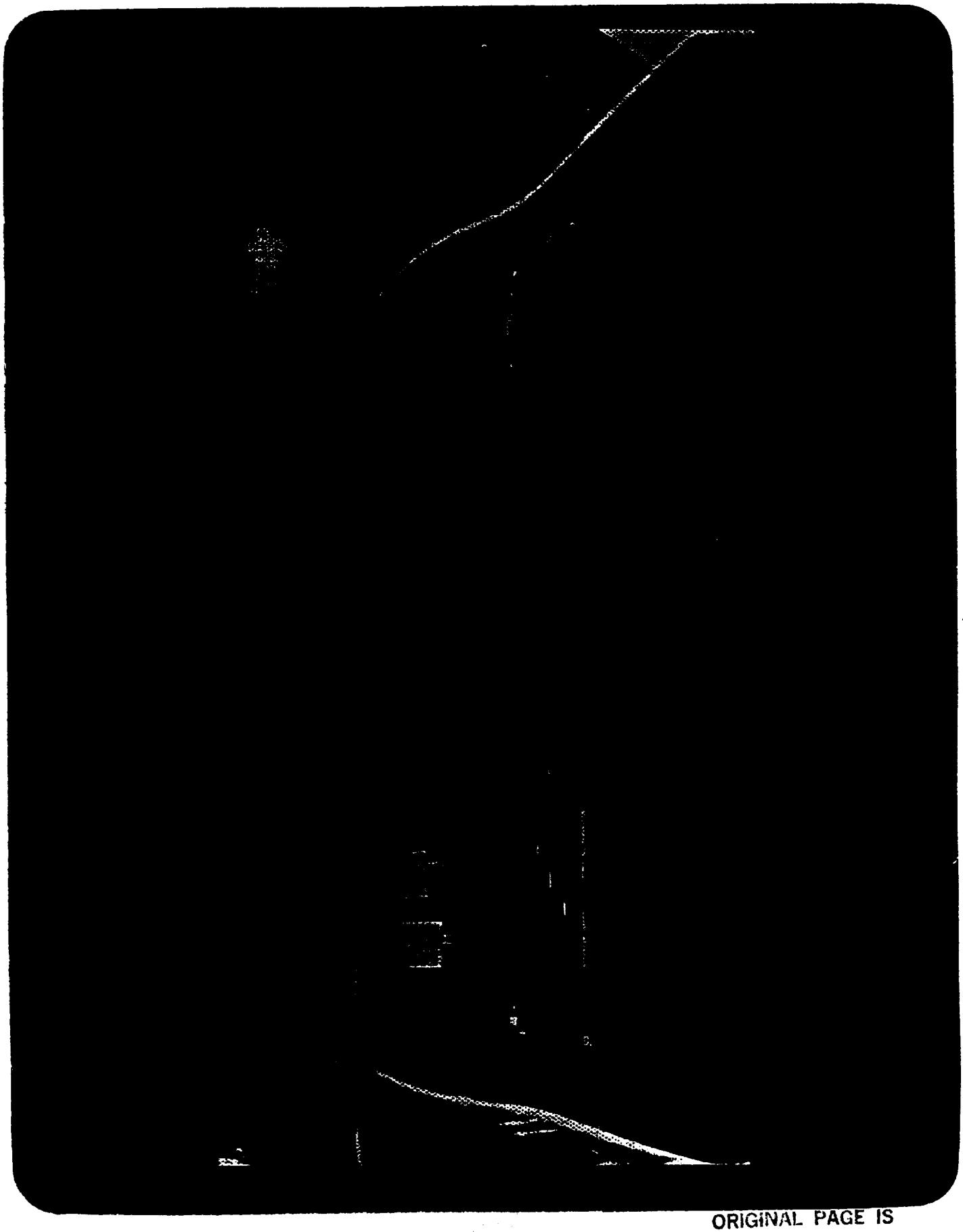
ALLOWABLE TOLLMIEN-SCHLICHTING DISTURBANCE AMPLIFICATION RATIOS AT MEASURED TRANSITION





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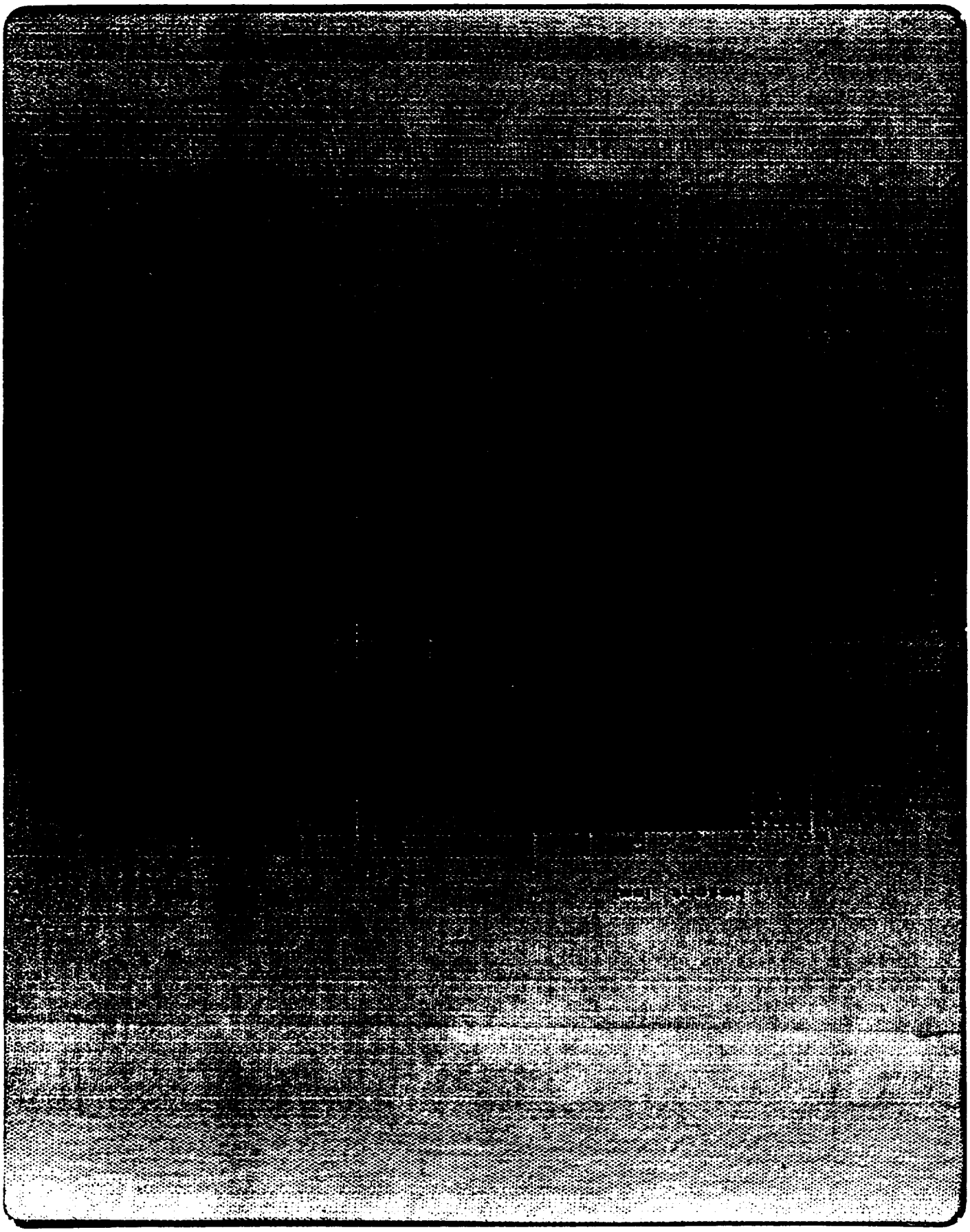

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CODE VALIDATION RESEARCH PROJECTS

- STORES INTEGRATION -

- 3-D CAVITIES
- DELTA WING WITH STORES
- TWO BODY INTERFERENCE

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CONCLUDING REMARKS

- CODE VALIDATION IS A PART OF MOST EVERYTHING WE DO.
- TEST TECHNIQUES AND INSTRUMENTATION COVER THE FULL SPECTRUM OF THE STATE-OF-THE-ART; NEW INVENTIONS ALLOW THE MEASUREMENT OF QUANTITIES NOT PREVIOUSLY MEASURED AND WITH HIGHER RESOLUTION.
- MORE EMPHASIS ON METHODS/INSTRUMENTS TO OBTAIN TIME VARYING 3-D DATA NEEDED.
- TEST AND CODE ERRORS NEED MORE CLARIFICATION AND/OR REDUCTION.

CONCLUDING REMARKS (CONTINUED)

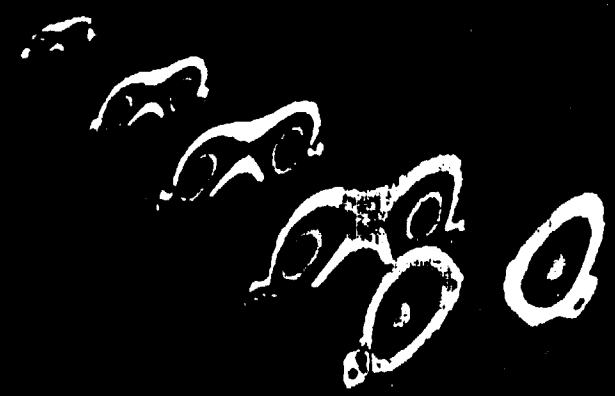
- CODE VALIDATION IS NOT A PROGRAM UNTO ITSELF BUT AN INTEGRAL PART OF BROADER PROGRAMS.

- THE UNNATURAL EMPHASIS ON OFF-SURFACE VERSUS SURFACE DATA DOESN'T MAKE SENSE. WE NEED BOTH KINDS. WHAT GETS DONE DEPENDS ON THE INSTRUMENTS AVAILABLE, THE TYPE OF RESEARCHERS AVAILABLE, THE TUNNEL TO BE USED, THE CODE TO BE VALIDATED AND THE PARTICULAR FLOW PHENOMENA OF INTEREST.

LOW SPEED AERODYNAMICS CFD CODE VALIDATION

JERRY C. SOUTH
HEAD/AMB

EXPERIMENT



CFL3D

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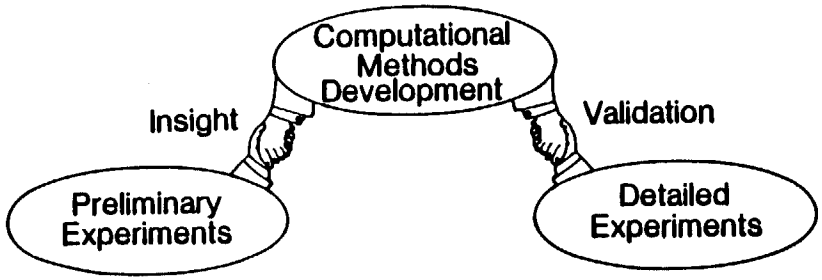
ANALYTICAL METHODS BRANCH

OBJECTIVE: Develop and Validate Analytical Methods for Low—Speed Aerodynamics



Experimental Needs For Computational Methods

"It is better to do one experiment with extreme thoroughness"

- Redundant Measurements with more than one Instrument
- Uncertainty Analysis
- Conducted in more than one Facility

Experimental Needs For Computational Methods

Well Documented Experiments Include:

- Complete Initial and/or Boundary Data
- Profiles of Mean Flow and Turbulence
- Record any of the Following:
  - Gross Unsteadiness
  - Vortex Shedding
  - Vortex Structures
  - Unexpected Flow Behavior

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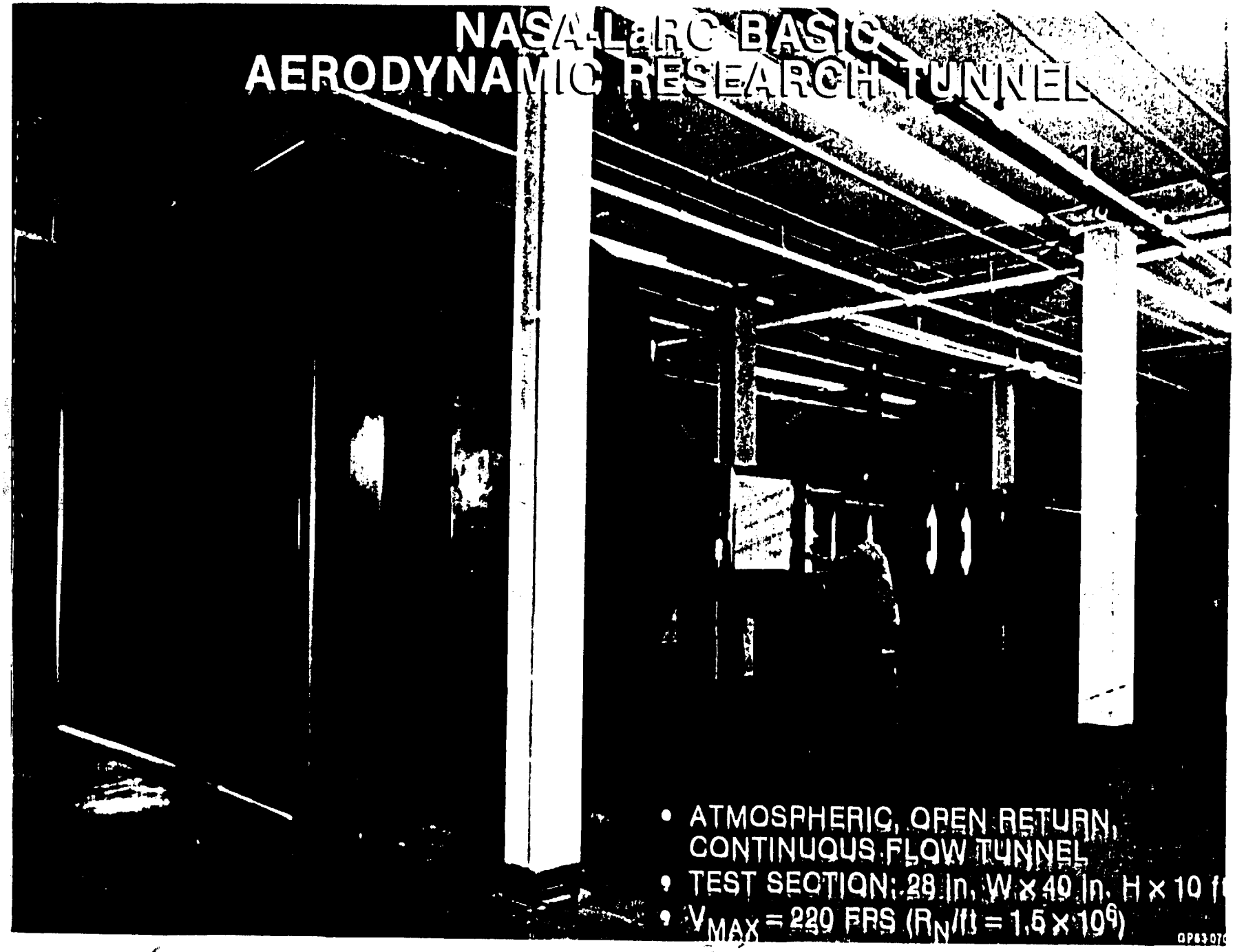

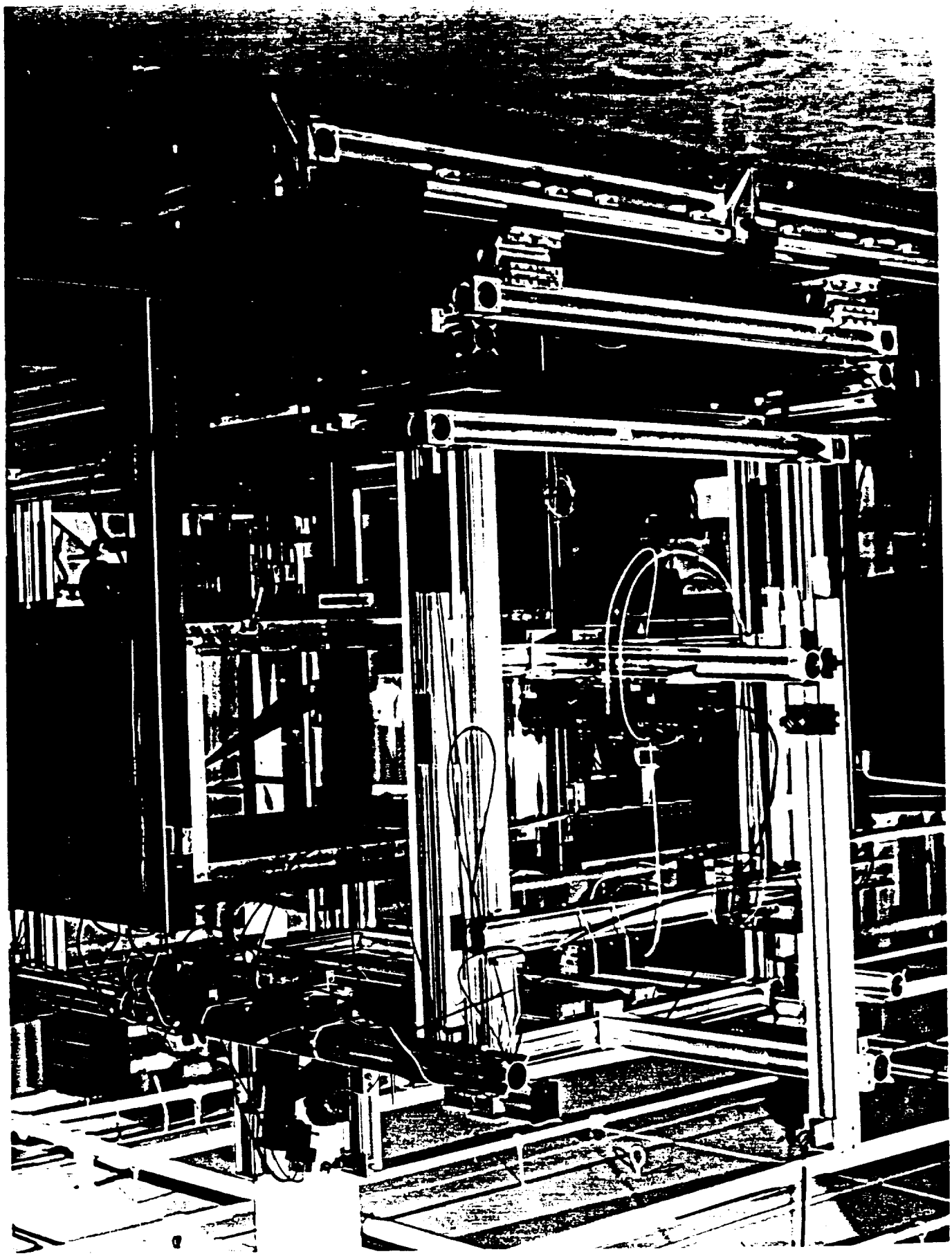

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BART INSTRUMENTATION

DATA ACQUISITION HIGHLY AUTOMATED

REAL-TIME DISPLAY OF FLOWFIELD QUANTITIES

KEY INSTRUMENTATION

- ELECTRONICALLY SCANNING PRESSURE SYSTEM
- 3 COMPONENT HOT WIRE SYSTEM
- 3 COMPONENT LASER VELOCIMETER

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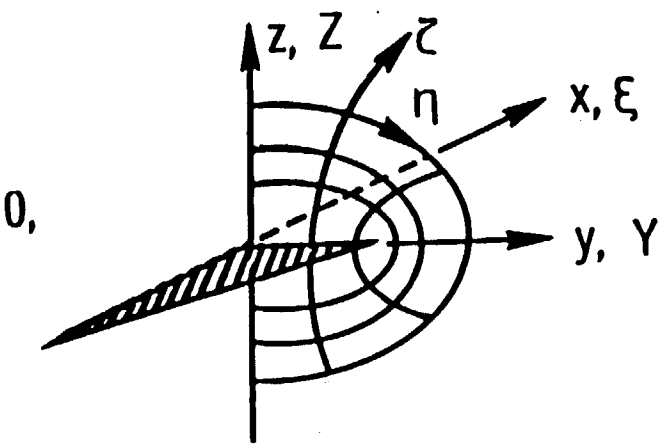
PLANNED CFD VALIDATION EXPERIMENTS
LSAD/AMB

EXPERIMENT	FACILITY	CODE
SWEPT DELTA WING		
75/76 DEGREE	LaRC/BART	CFL3D/Thomas
65 DEGREE	LaRC/BART/LTPT/NTF	VOR3DI/Liu
5 DEGREE CONE	LaRC/BART	CFL3D/Thomas
REARWARD-FACING STEP	LaRC/BART/VTWT ARC/FML	LES/Kim

COMPUTATIONAL METHOD

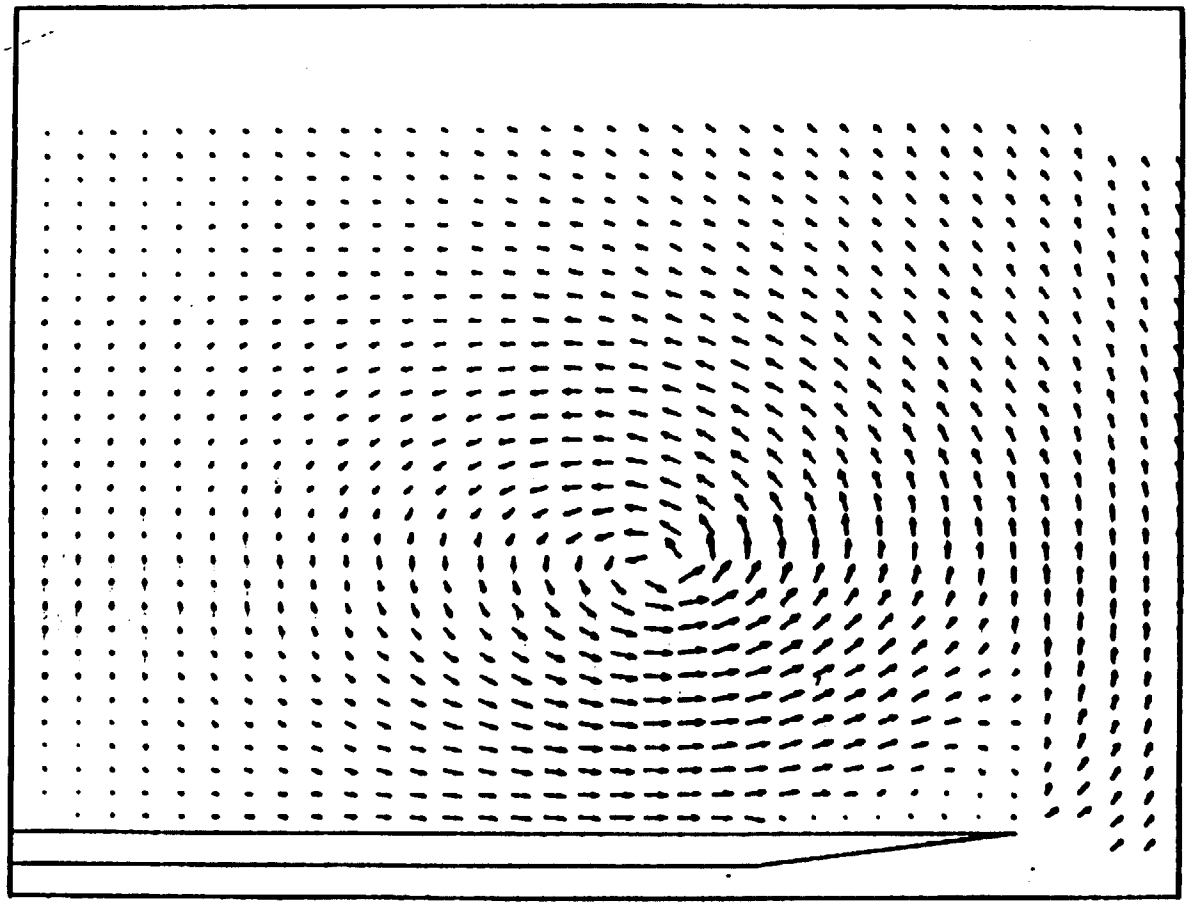
$$\frac{\delta \hat{Q}}{\delta t} + \frac{\delta \hat{F}}{\delta \xi} + \frac{\delta \hat{G}}{\delta \eta} + \frac{\delta(\hat{H} - \hat{H}_V)}{\delta \zeta} = 0,$$



- Time-dependent conservation law form of compressible Navier-Stokes equations (thin-layer)
- Upwind-biased spatial differencing
  - Upwind (flux split) for convective pressure
  - Central for shear stress/heat transfer
- Implicit, vectorizable time differencing with multigrid acceleration to steady-state
- Implemented in finite-volume form

75 DEGREE DELTA WING – EXP

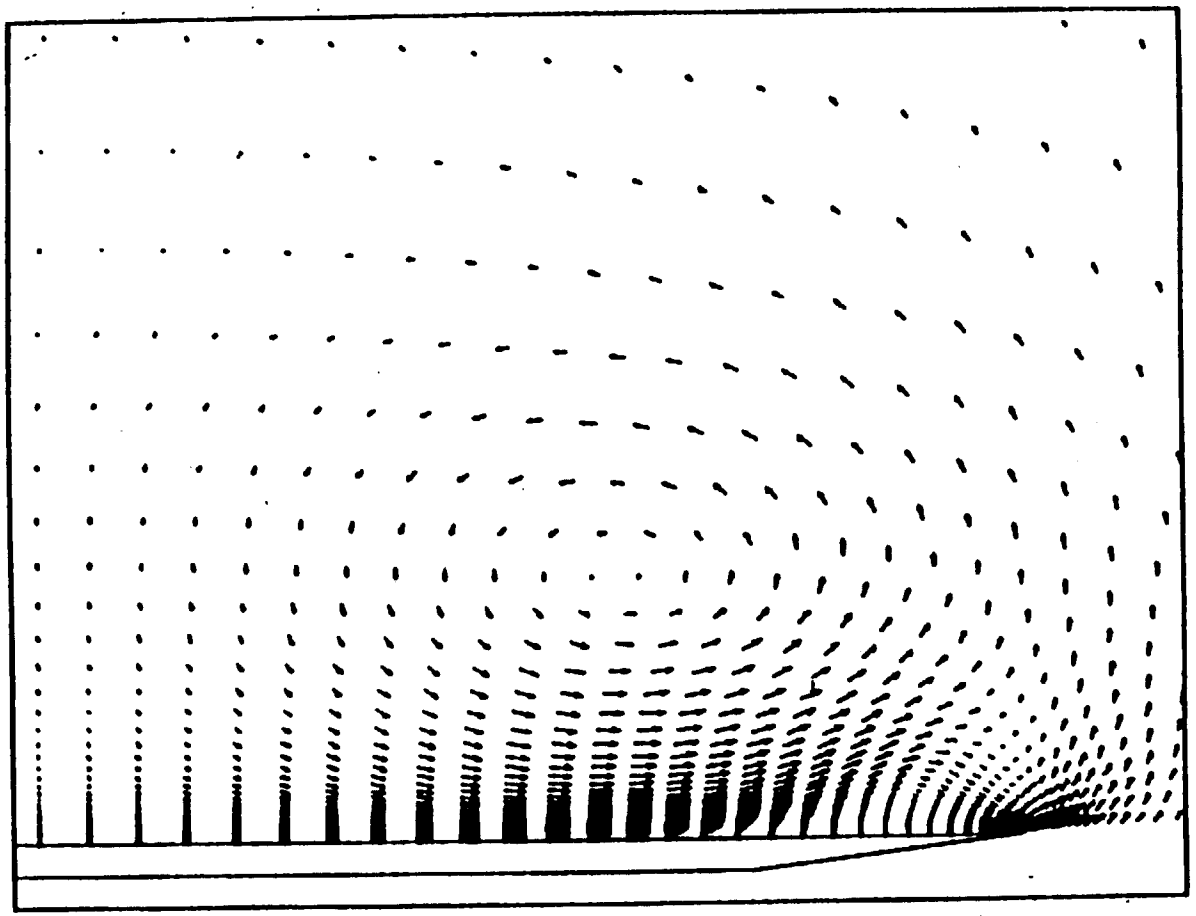
CROSS FLOW VELOCITY VECTORS



ALPHA = 20.5° Rn = .5E6 x/L = .9

75 DEGREE DELTA WING – CFL3D

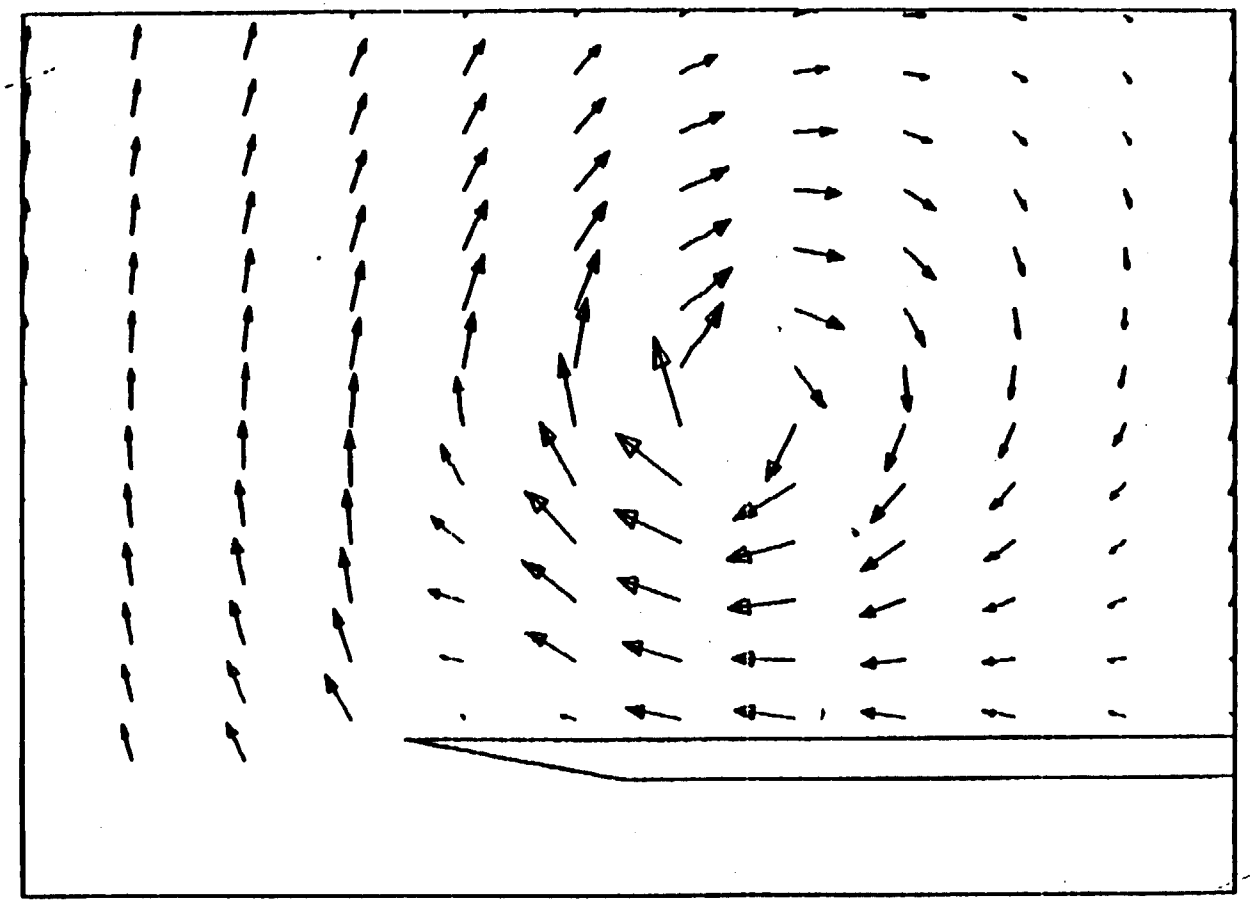
CROSS FLOW VELOCITY VECTORS



ALPHA = 20.5° Rn = .5E6 x/L = .9

75 DEGREE DELTA WING

CROSS FLOW VELOCITY VECTORS

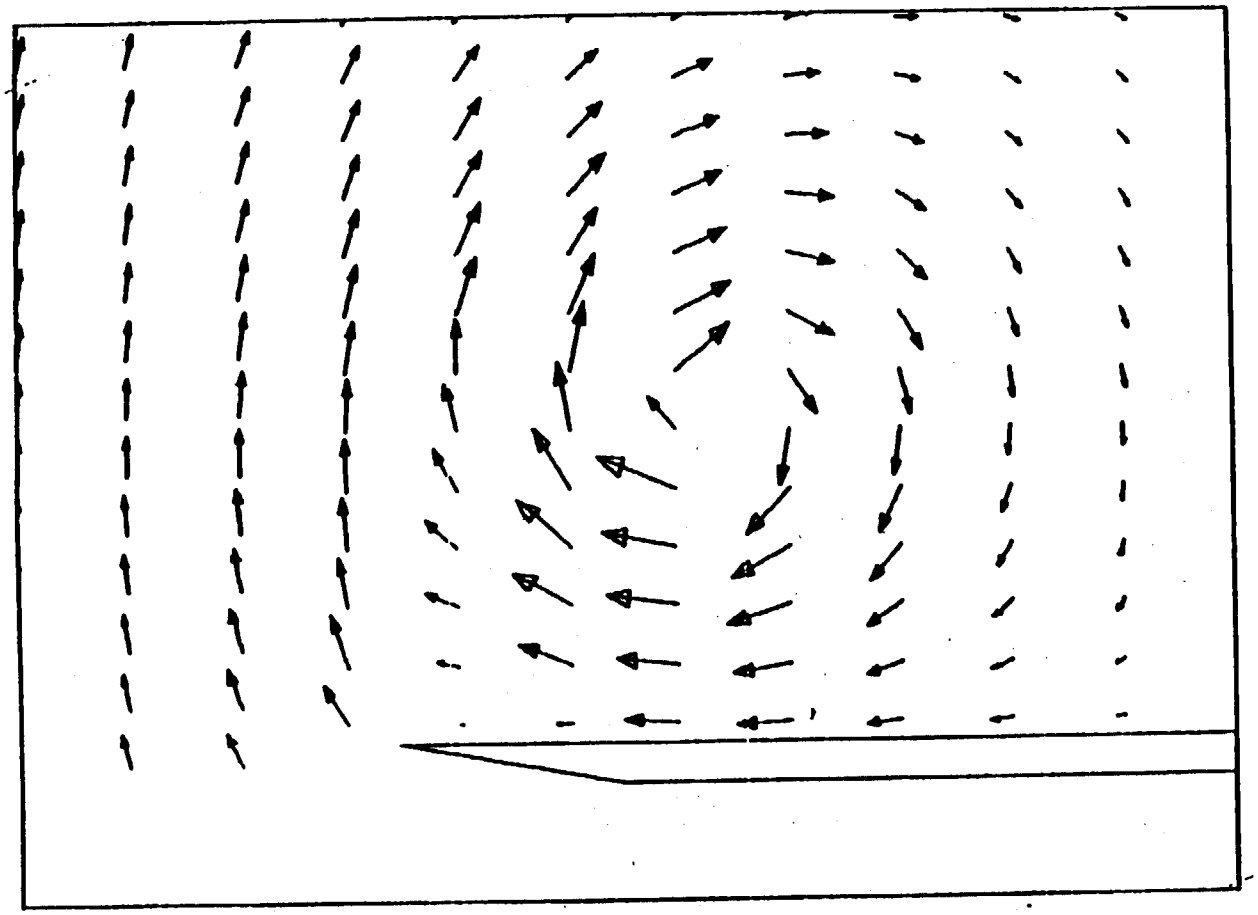


ALPHA = 20.5° Rn = 1.E6 x/L = .9

5 – HOLE PROBE RESULTS

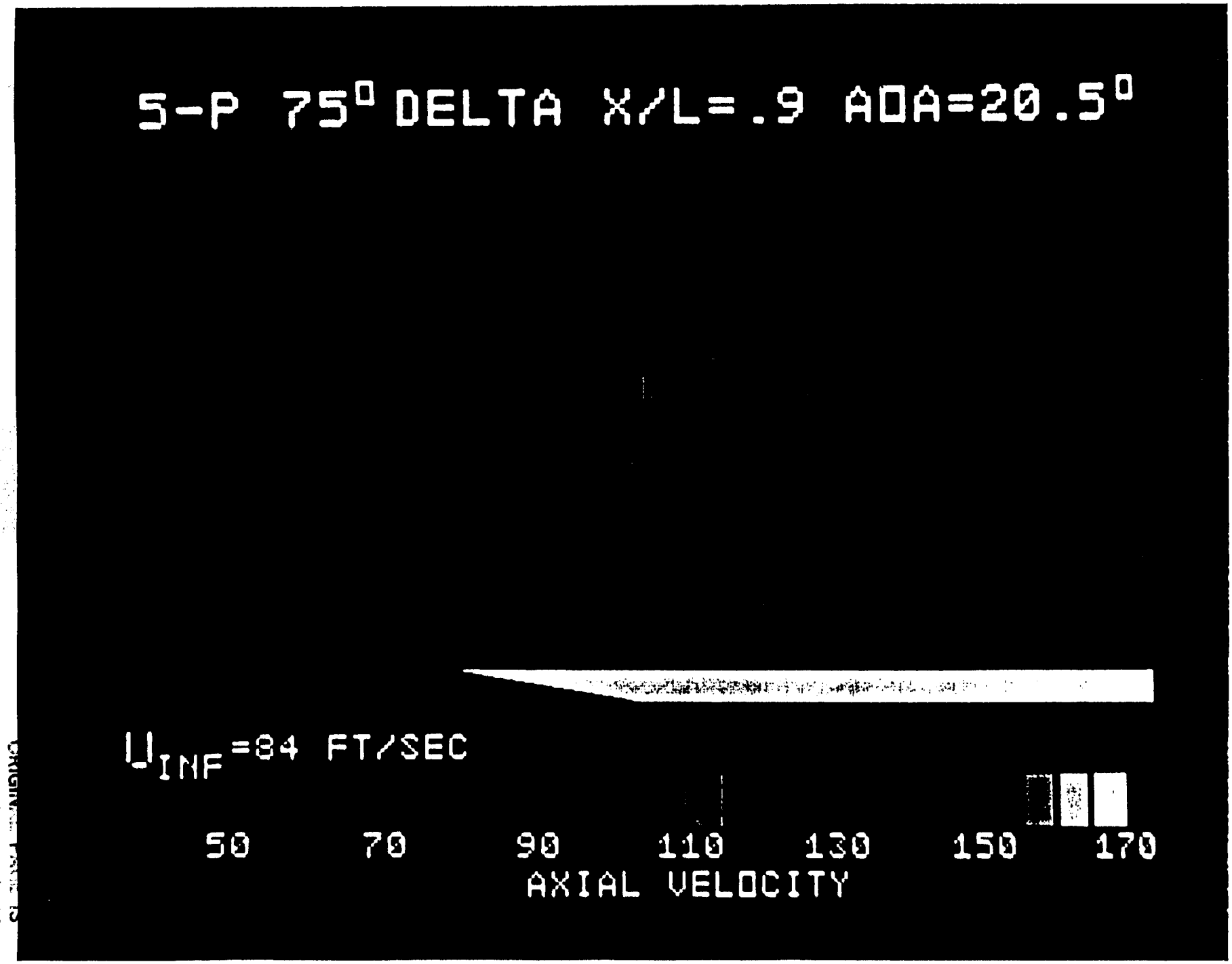
75 DEGREE DELTA WING

CROSS FLOW VELOCITY VECTORS



ALPHA = 20.5° Rn = 1.E6 x/L = .9

LDV RESULTS



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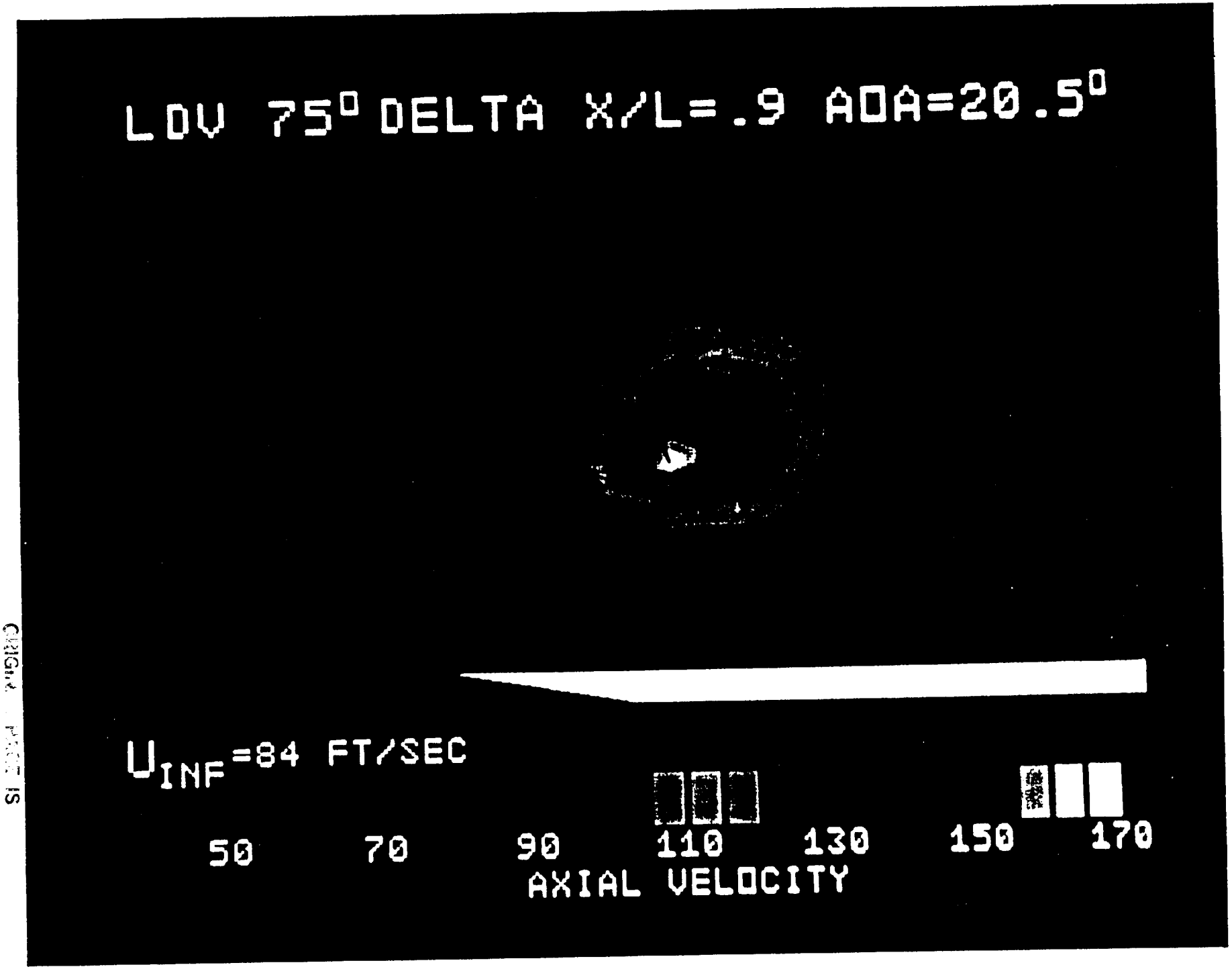

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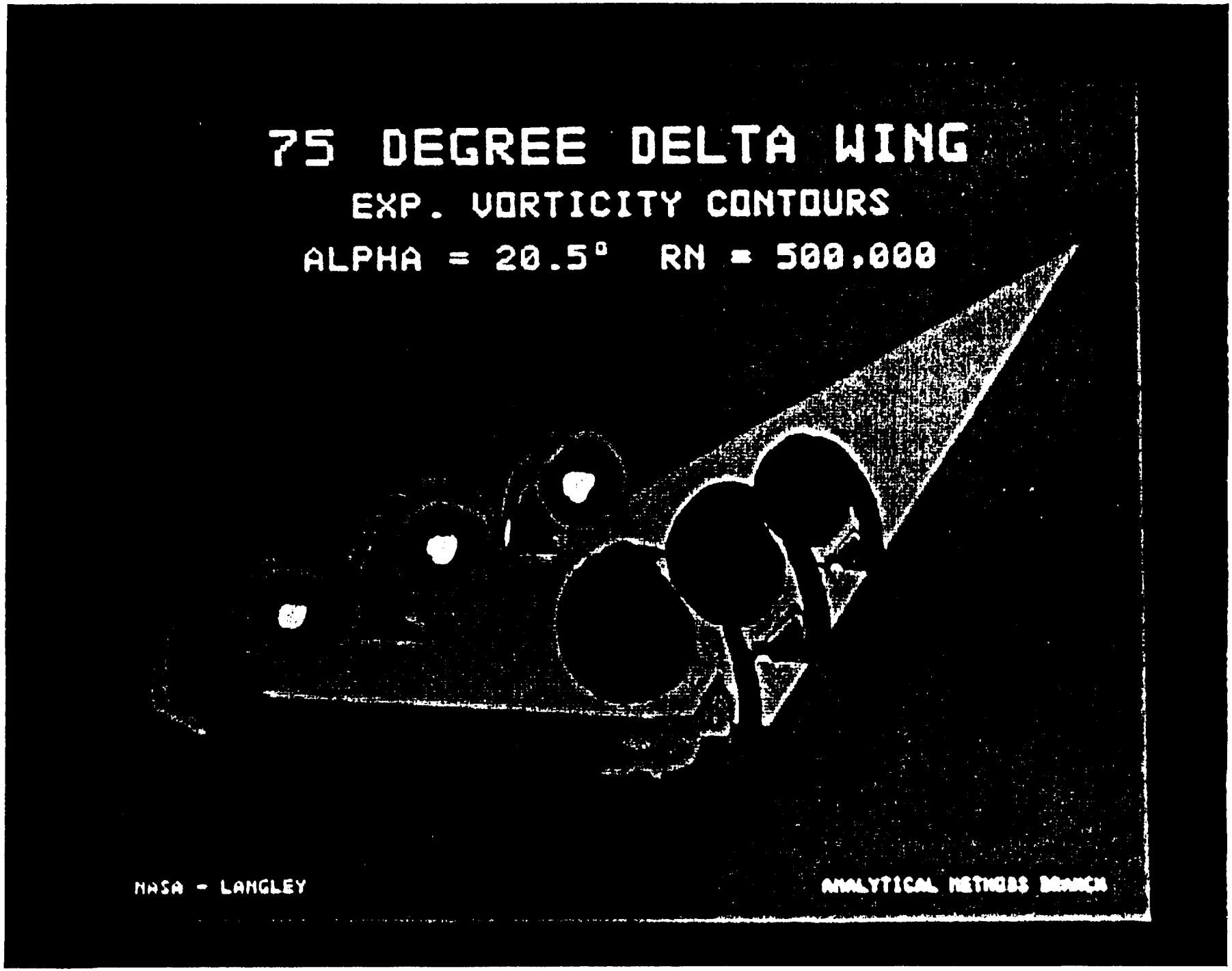
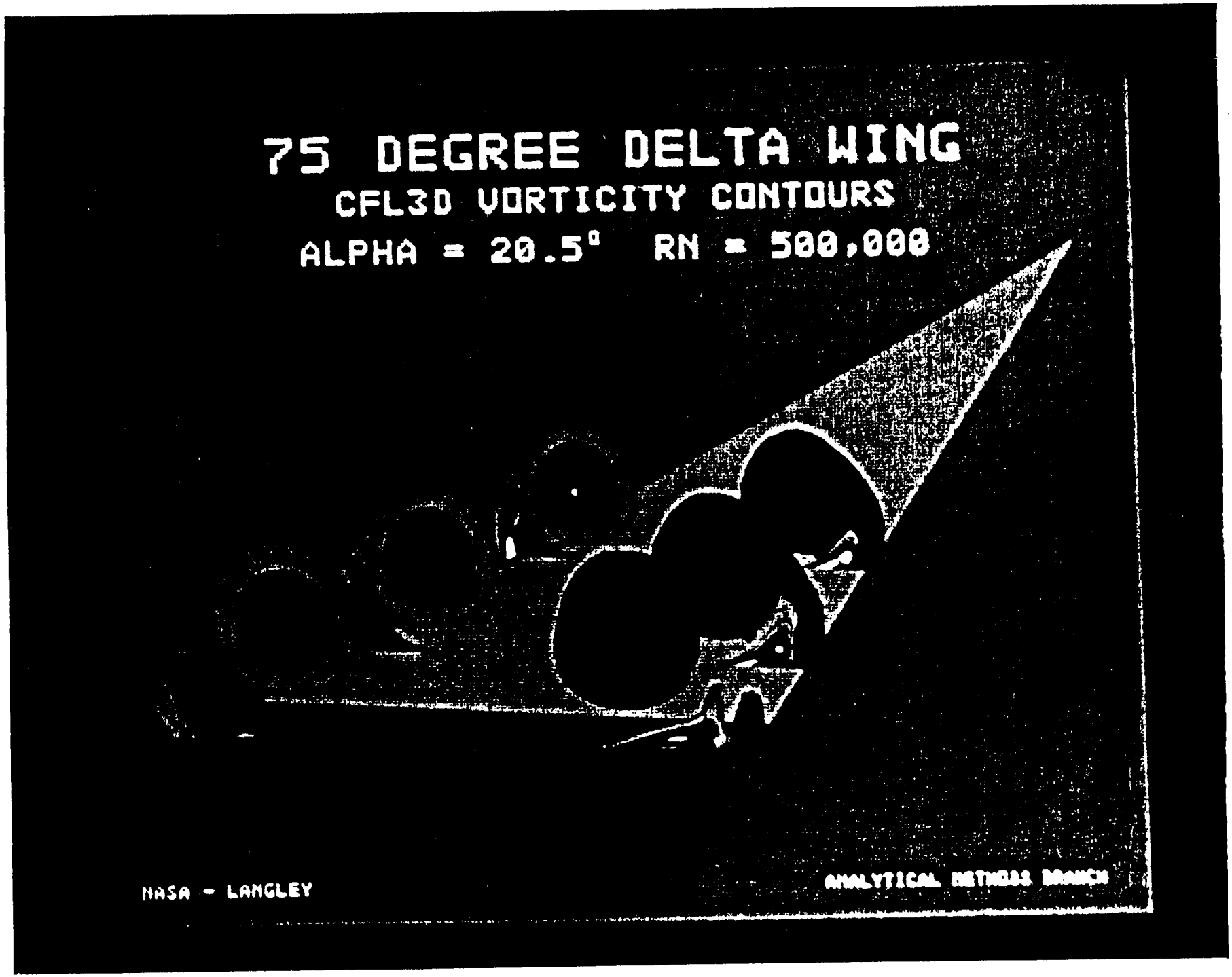
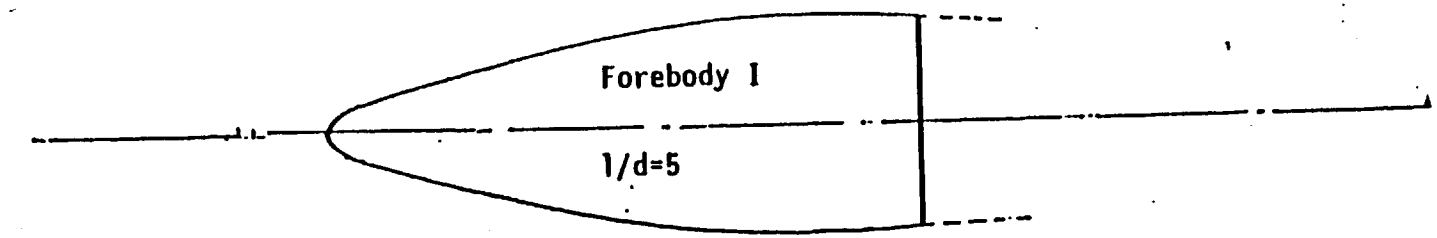

75 DEGREE DELTA WING
EXP. VORTICITY CONTOURS
ALPHA = 20.5° RN = 500,000
NASA - LANGLEY
ANALYTICAL METHODS BRANCH

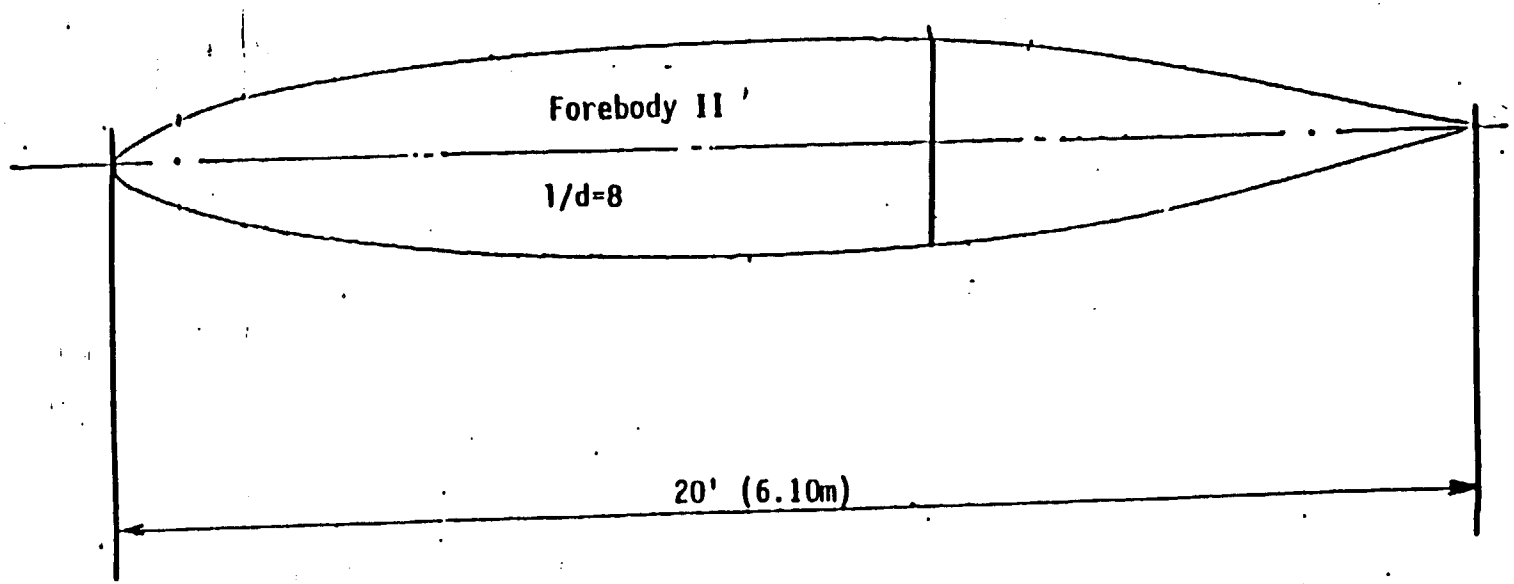

75 DEGREE DELTA WING
CFL3D VORTICITY CONTOURS
ALPHA = 20.5° RN = 500,000
NASA - LANGLEY
ANALYTICAL METHODS BRANCH

OTHER RESEARCH ACTIVITIES

EXPERIMENT	CODE
HELICOPTER ROTOR INFLOW	UTRC/CAMRAD/Hoad
LAMINAR STABILITY	
20 FT NLF BODY	CFL3D/Thomas
SURFACE IMPERFECTIONS	VPI/Nayfeh
CRESCENT/SHEARED PLANFORMS	

NLF BODY EXPERIMENT





HIGH-SPEED CODE VALIDATION

RICHARD W. BARNWELL
R. CLAYTON ROGERS
JAMES L. PITTMAN
DOUGLAS L. DWOYER
NASA LANGLEY RESEARCH CENTER
HAMPTON, VIRGINIA

JULY 14, 1987

N92-70931

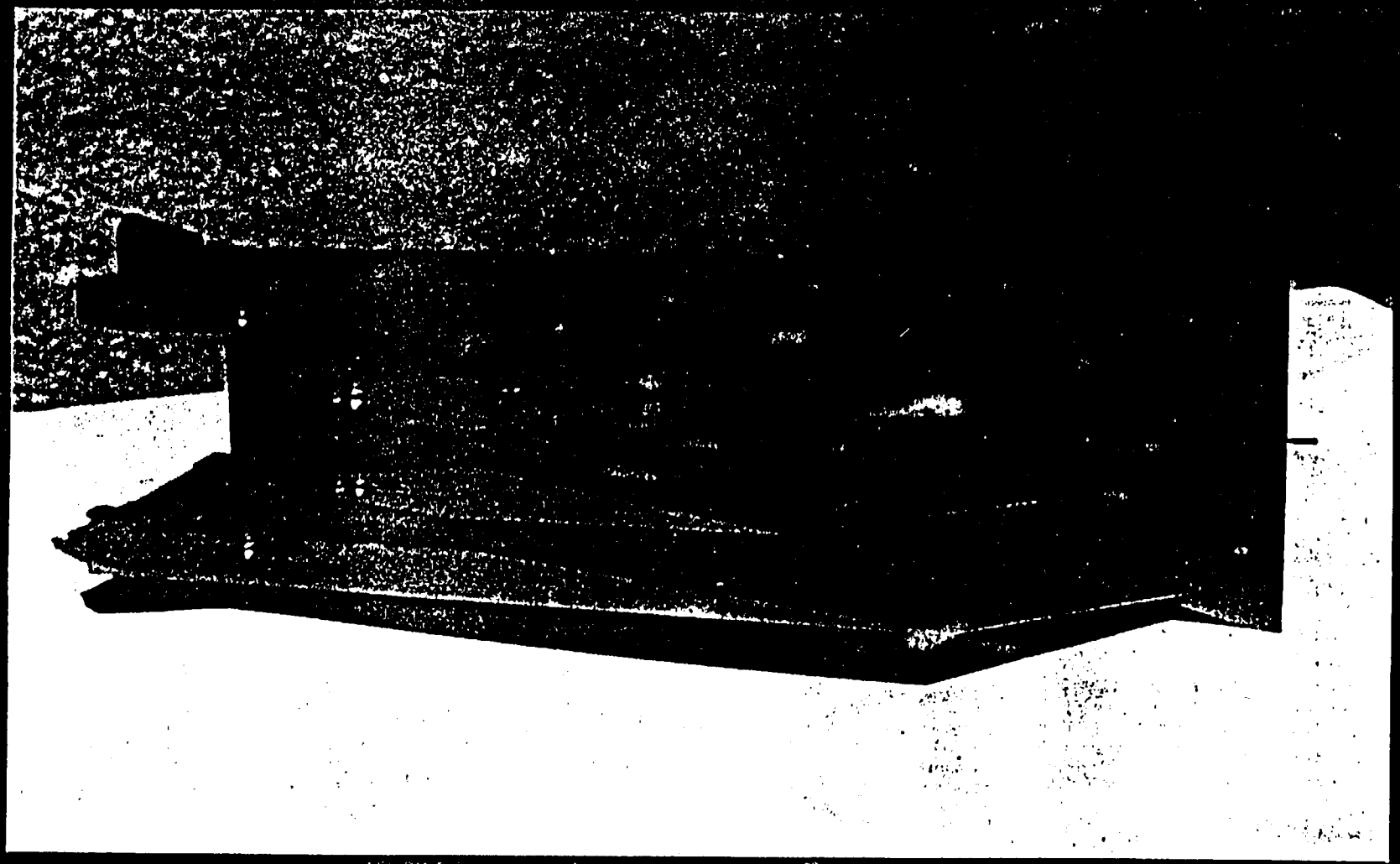
HIGH-SPEED VALIDATION PROBLEMS

- 3 VELOCITY COMPONENTS NOT ADEQUATE FOR NONPOTENTIAL FIELD DATA
  - 2 THERMODYNAMIC VARIABLES NEEDED FOR EQUILIBRIUM FLOW
  - ADDITIONAL THERMODYNAMIC DATA NEEDED FOR NONEQUILIBRIUM FLOW
- ADDITIONAL PHENOMENA INVOLVED
  - HEATING
  - CHEMISTRY (COMBUSTION)
  - THERMAL RADIATION
- MEASUREMENT COMPLICATIONS
  - HIGH-SPEED SEEDING PROBLEMS
  - PROBE SURVIVABILITY PROBLEMS (LOADS AND HEATING)
  - SHORT RUN TIMES
- RESURGENCE IN DIAGNOSTIC MEASUREMENTS FOR HIGH SPEEDS ABOUT ONE DECADE BEHIND THAT FOR LOW AND TRANSONIC SPEEDS

3-D EULER/NAVIER-STOKES INLET CODE

- Solves governing equations in conservation form by MacCormack's explicit or explicit/implicit method
- Uses boundary-fitted curvilinear coordinates
- Uses Baldwin-Lomax algebraic turbulence model
- Operational on VPS-32 vector processing computer at NASA Langley
- Fully vectorized in STAR FORTRAN with 32-bit word arithmetic
- Can use up to 2.8 million grid points without going out of primary memory of the computer and has a compute rate of $.7 \times 10^{-5}$ sec/grid point for one complete time-step

TWO-STRUT INLET CONFIGURATION



FLOW CONDITIONS AND GRID

$M_\infty = 4.03$

$P_\infty = 8724\ N/M^2$

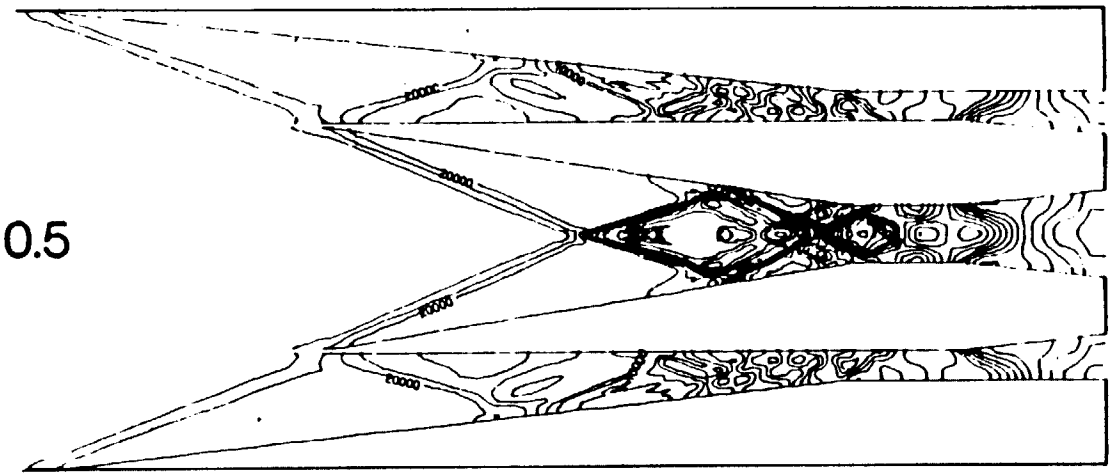
$T_\infty = 70\ K$

(TURBULENT FLOW AT ZERO ANGLE OF ATTACK)

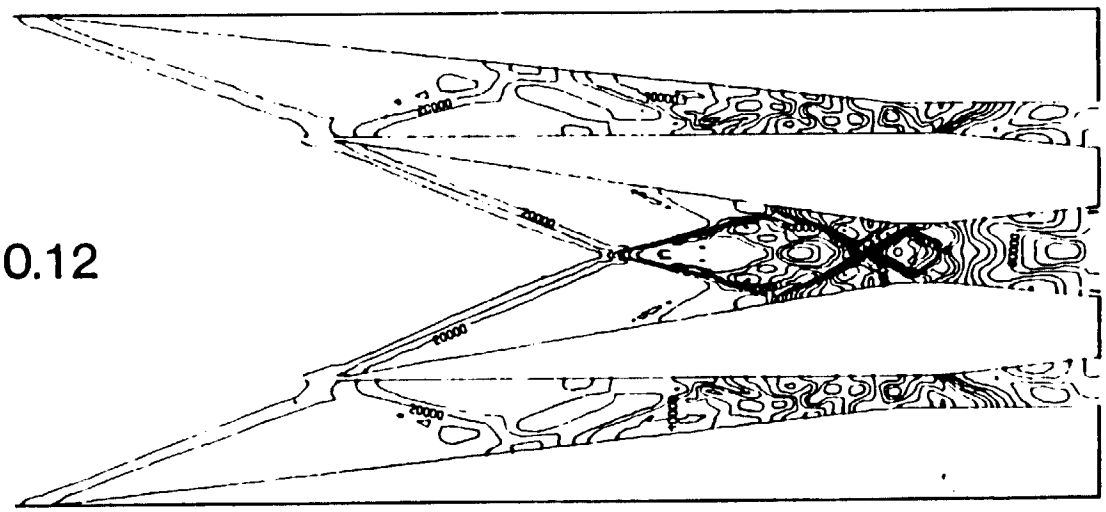
GRID SIZE: 77 X 69 X 51 (APPROXIMATELY 271,000) FOR HALF CONFIGURATION

PRESSURE CONTOURS IN TWO LONGITUDINAL PLANES

$\frac{z}{H} = 0.5$

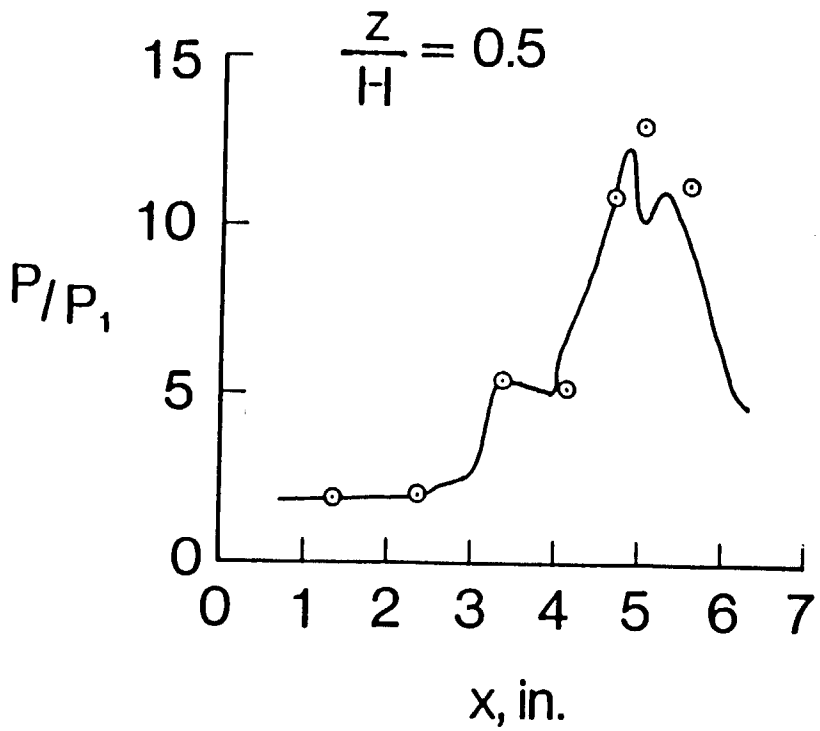


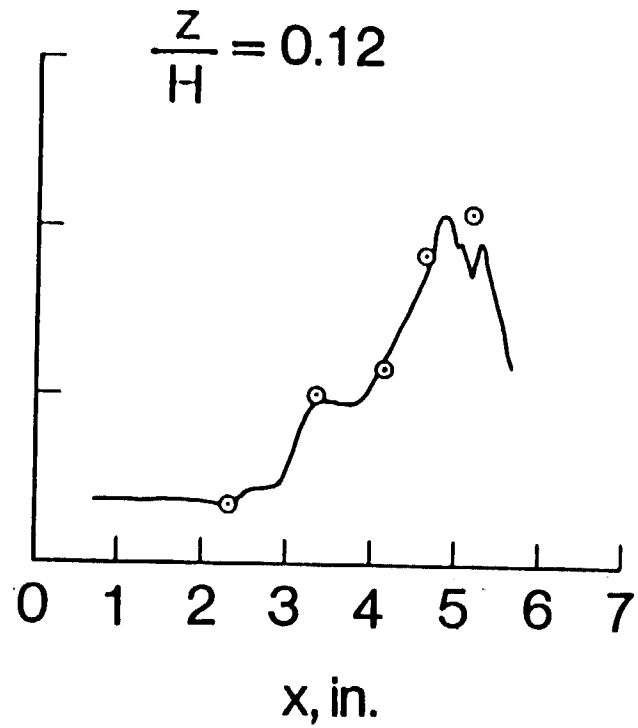
$\frac{z}{H} = 0.12$



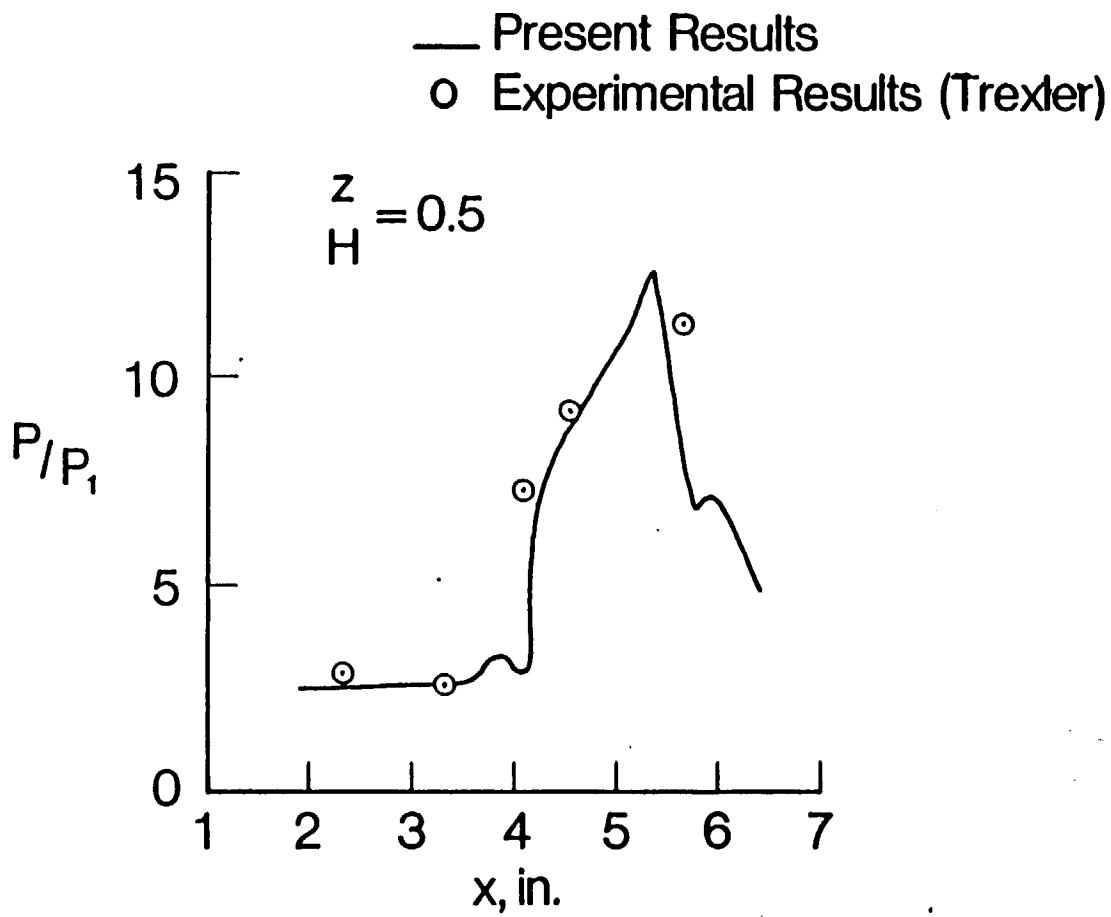
SIDEWALL PRESSURE DISTRIBUTION

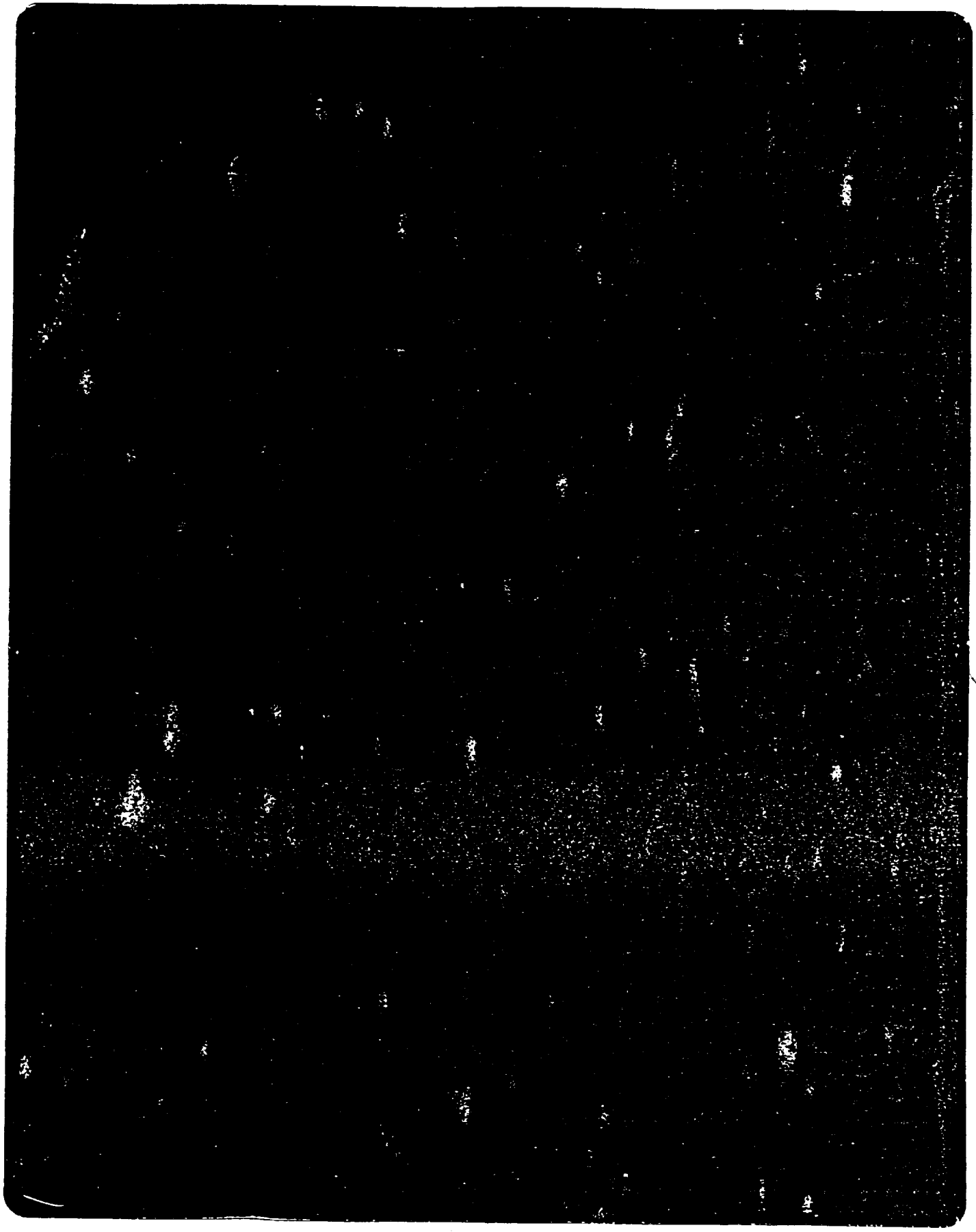
—— Present Results
o Experimental Results (Trexler)





PRESSURE DISTRIBUTION ON STRUT INNER SURFACE





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PARAMETRIC ENGINE MODEL

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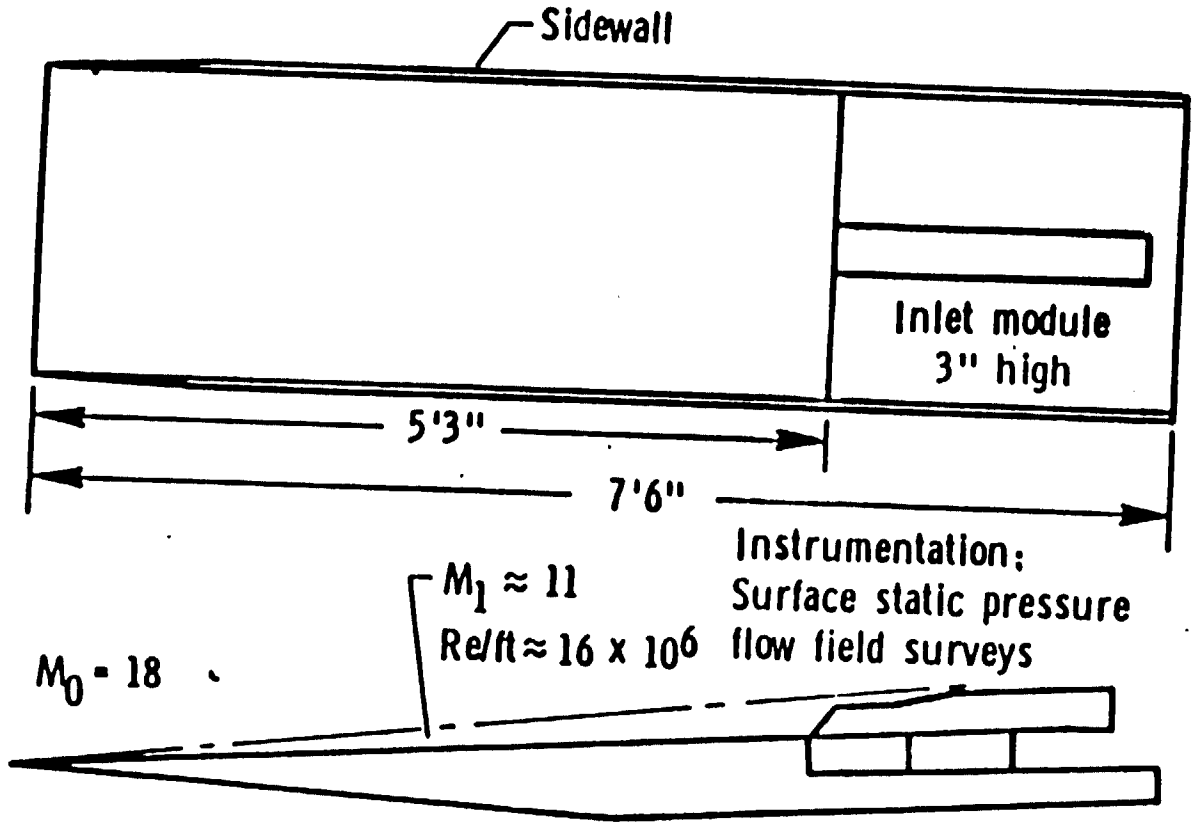
INLET/FOREBODY TESTS IN 60" HELIUM TUNNEL

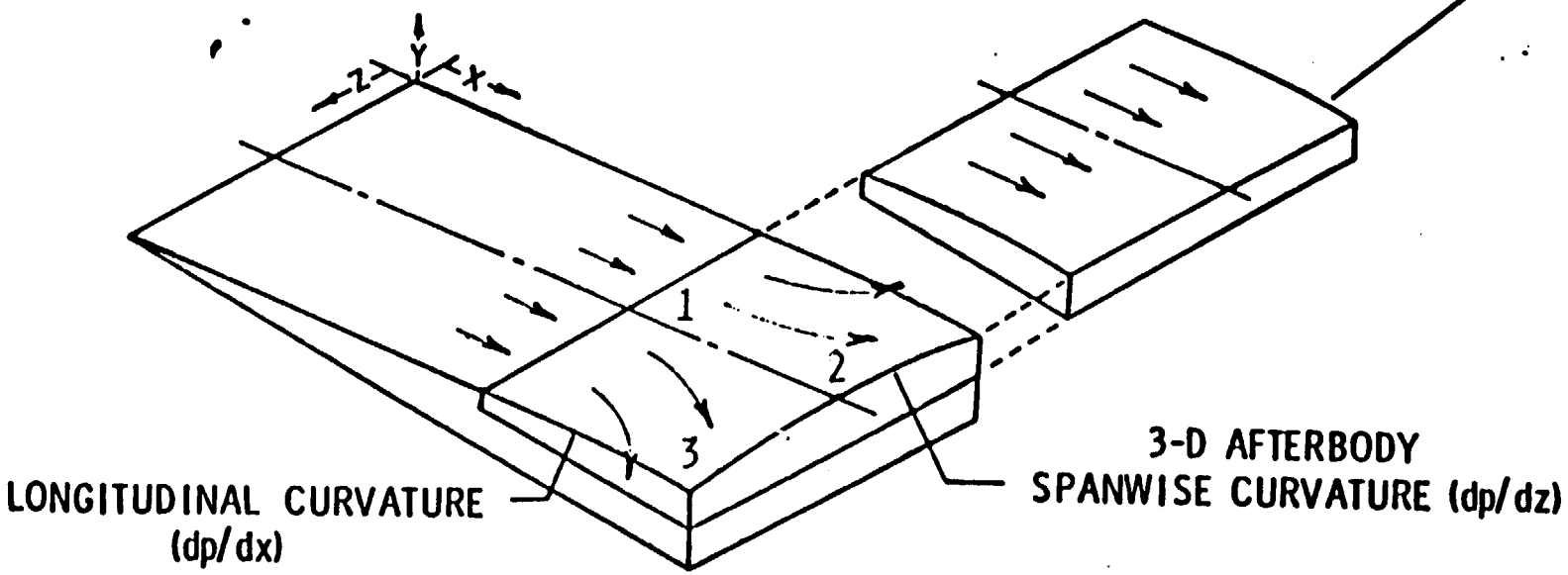


4^0 N_2 Cooled foreplate, $T_W/T_T = .35$ to 1.0

Transitional and turbulent boundary layer characterized in NASA TP 1243.

- $R_L > 100 \times 10^6$

$\delta = 5$ cm at beginning of expansion

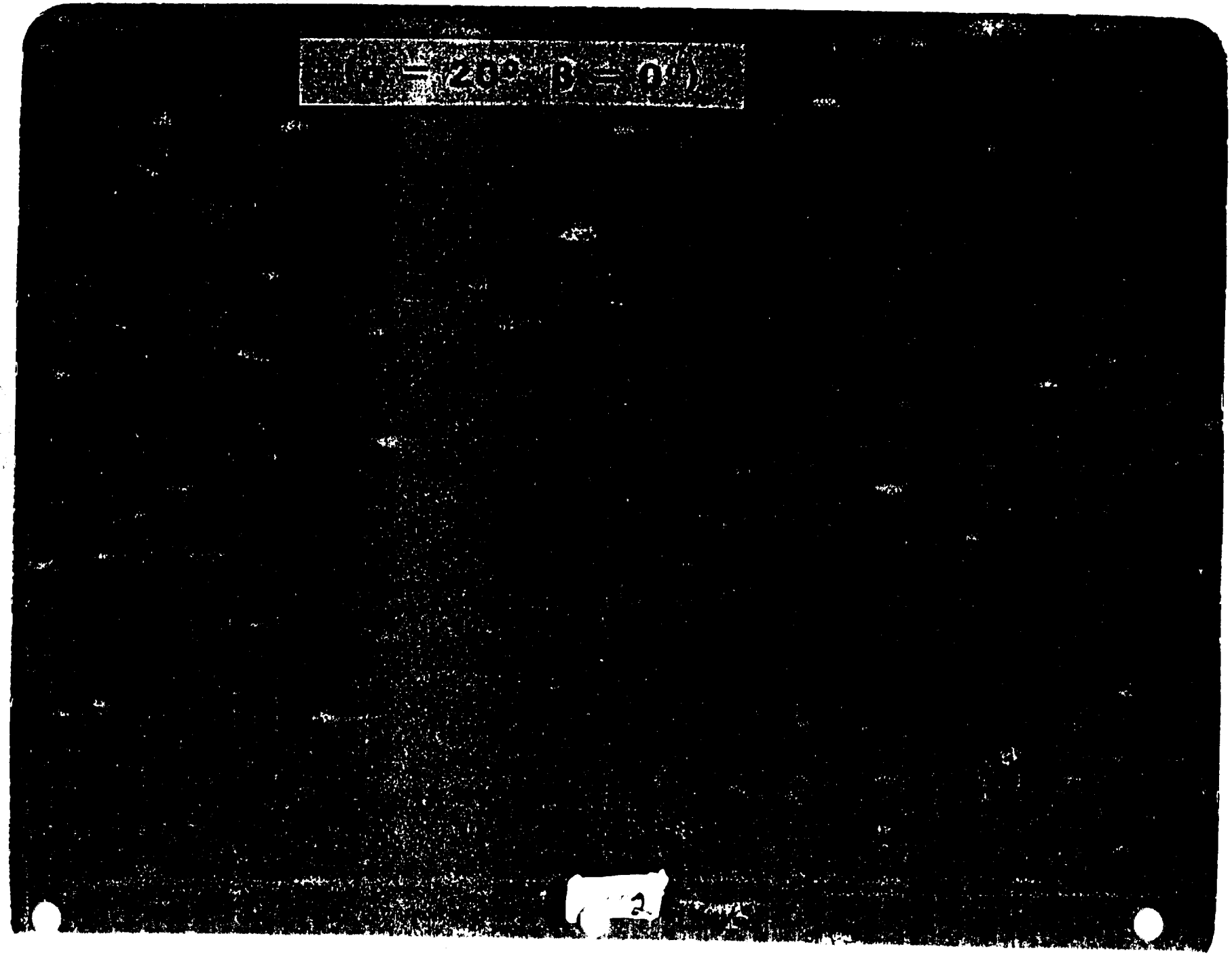


MEASUREMENTS
SURFACE PRESSURES
SURFACE HEAT TRANSFER
MEAN FLOW BOUNDARY LAYER SURVEYS
- PITOT
- TOTAL TEMPERATURE
- FLOW ANGULARITY

$M_\infty = 18$
$M_1 = 11.2$
$M_2 = 14.5$
$M_3 = 18$

National Aeronautics and
Space Administration

NO _____



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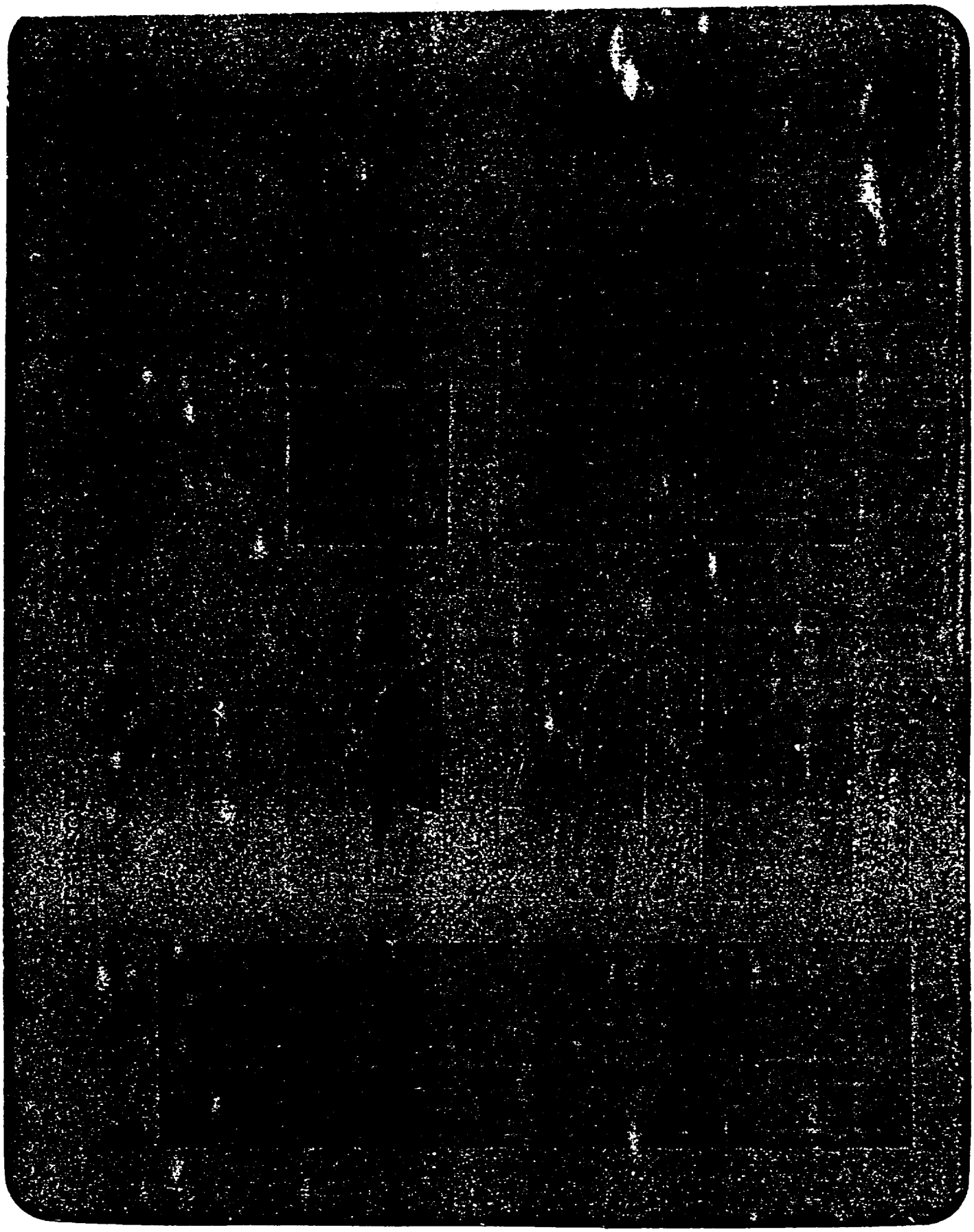

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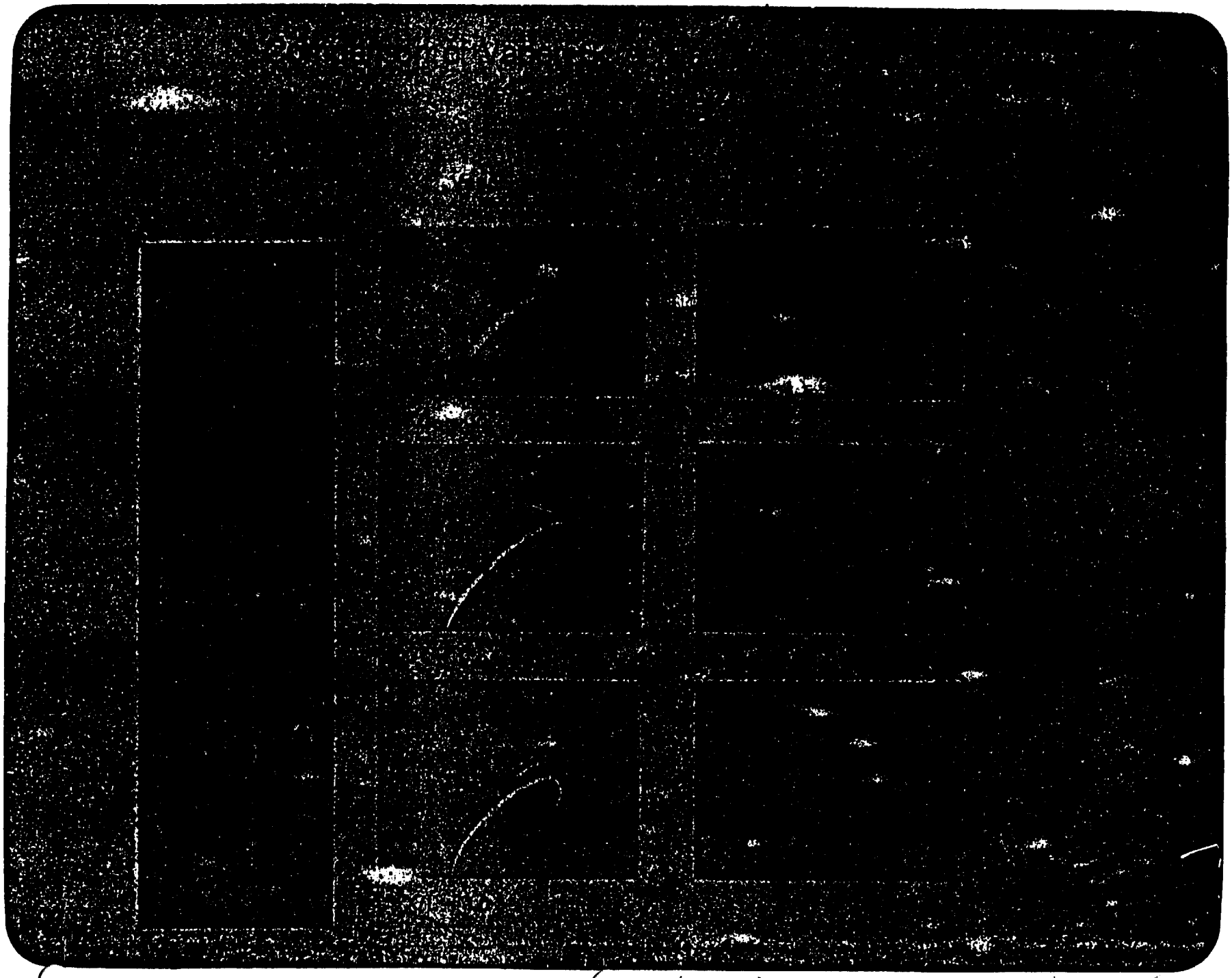
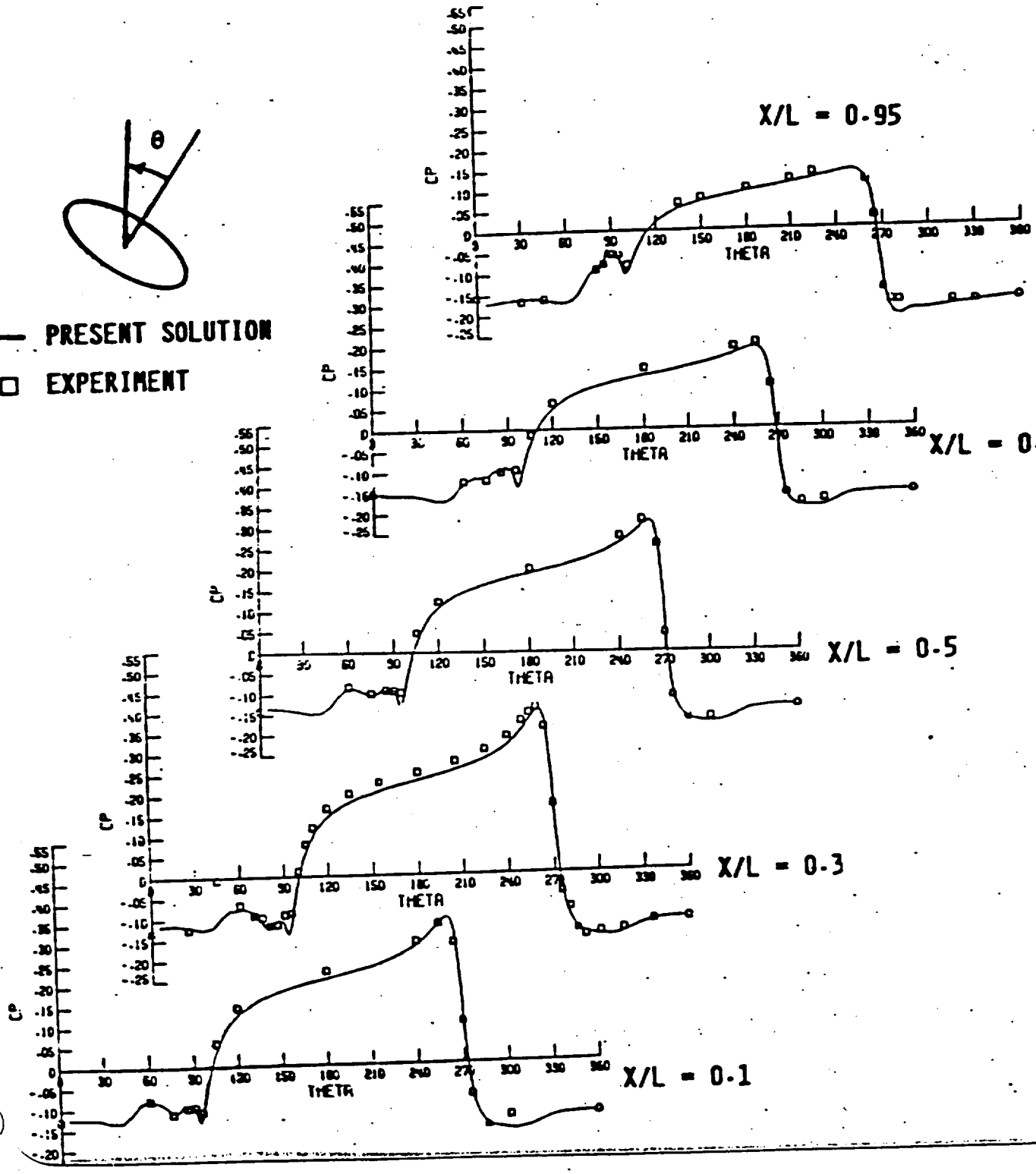


PRESSURE DISTRIBUTIONS ON ELLIPTICAL MISSILE

MACH NUMBER = 2.5

ANGLE OF ATTACK = 20°

ANGLE OF ROLL = 45°



225

Kumar

(15)

DEVELOPMENT OF CFD CODE

- GOVERNING EQUATIONS
  - 3-D REYNOLD'S AVERAGED FULL N-S EQUATIONS (5 EQUATIONS FOR U, V, W, ρ, AND E)
  - EQN. OF STATE (P)
  - SPECIES TRANSPORT EQUATIONS (1 TO 4 EQUATIONS)
- TURBULENCE MODEL
  - BALDWIN-LOMAX EDDY-VISCOSITY MODEL
- COMBUSTION MODEL
  - GLOBAL FINITE RATE H_2-AIR REACTION MODEL (ROGERS-CHINITZ MODEL)

NUMERICAL SOLUTION

- MacCORMACK'S EXPLICIT METHOD
  - IMPLICIT TREATMENT IN COMBUSTION SOURCE TERMS

VALIDATIONS OF CODE (PRELIMINARY)

- Need detailed experimental data of supersonic reacting flows (species concentration, temperature, pressure profiles)

- Piecewise validations for important flow features using available experimental data

  - Flow features behind rearward facing step
  - H_2-air non-reactive mixing flow over a flat plate
  - Fuel-air mixing detail near transverse injector

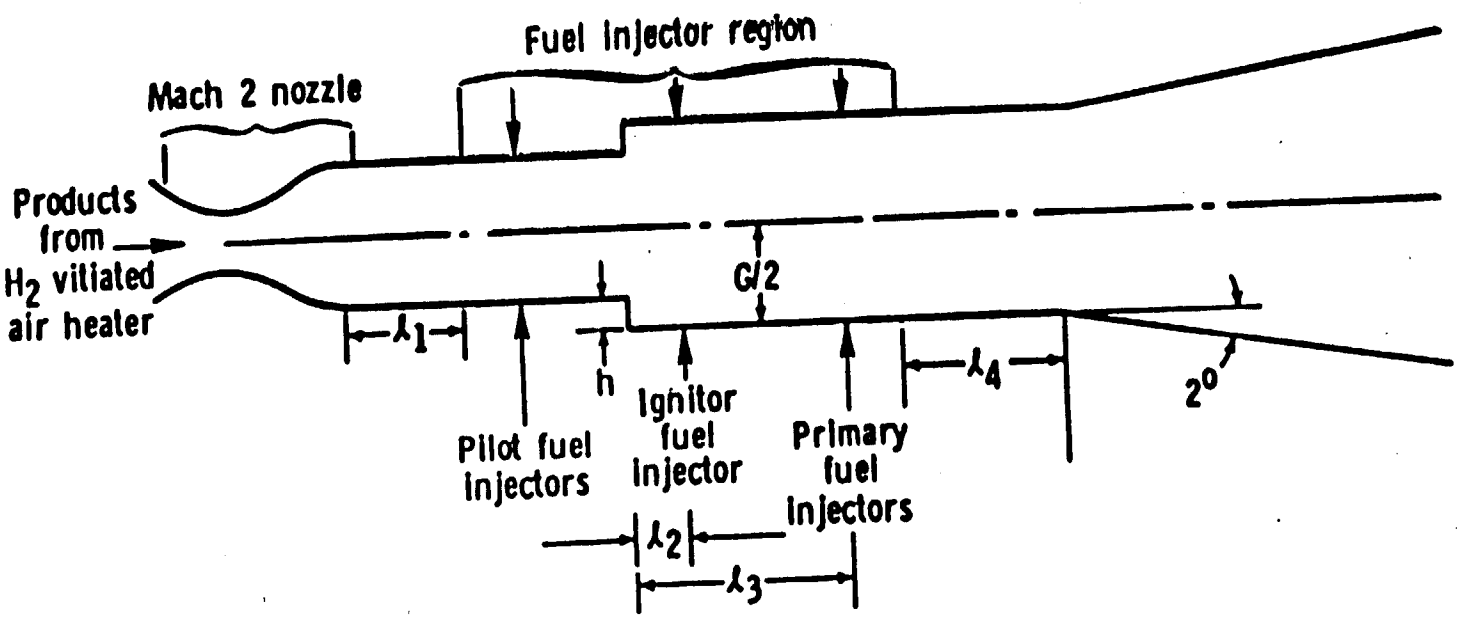
DIRECT-CONNECT COMBUSTOR EXPERIMENTS FOR EVALUATION OF CFD CODES

- EXPERIMENTAL VARIABLES
  - FUEL INJECTOR ARRANGEMENT
  - PHYSICAL SCALE OF COMBUSTOR DUCT
  - BOUNDARY LAYER THICKNESS
  - AREA DISTRIBUTION
  - FUEL CHEMISTRY FROM H_2 TO CH_4
- DATA SOURCES
  - WALL PRESSURES, HEAT TRANSFER
  - FUEL MIXING BY LASER SCATTERING FROM SOLID COMBUSTION PRODUCTS (SiO_2) IN THE FUEL
  - POTENTIAL USE OF "HARDENED" CARS SYSTEM FOR TEMPERATURE PROFILES
- CFD APPLICATION
  - 3-D FULL N.S. CODE IN NEAR FIELD OF FUEL INJECTORS WHERE FLOW ELLIPTIC
  - 3-D P.N.S. CODE WHERE FLOW PREDOMINANTLY PARABOLIC

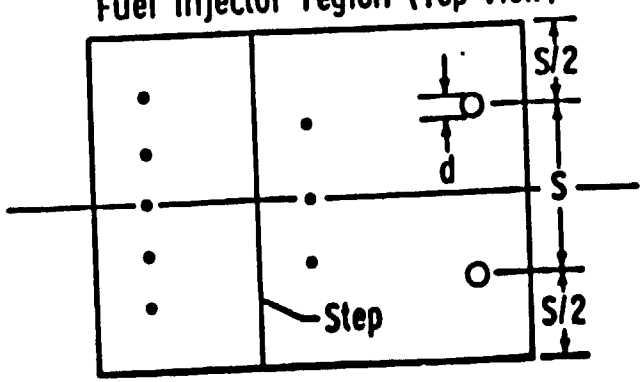
BOTH USE TWO-STEP H_2-AIR CHEMISTRY AND ALGEBRAIC TURBULENCE

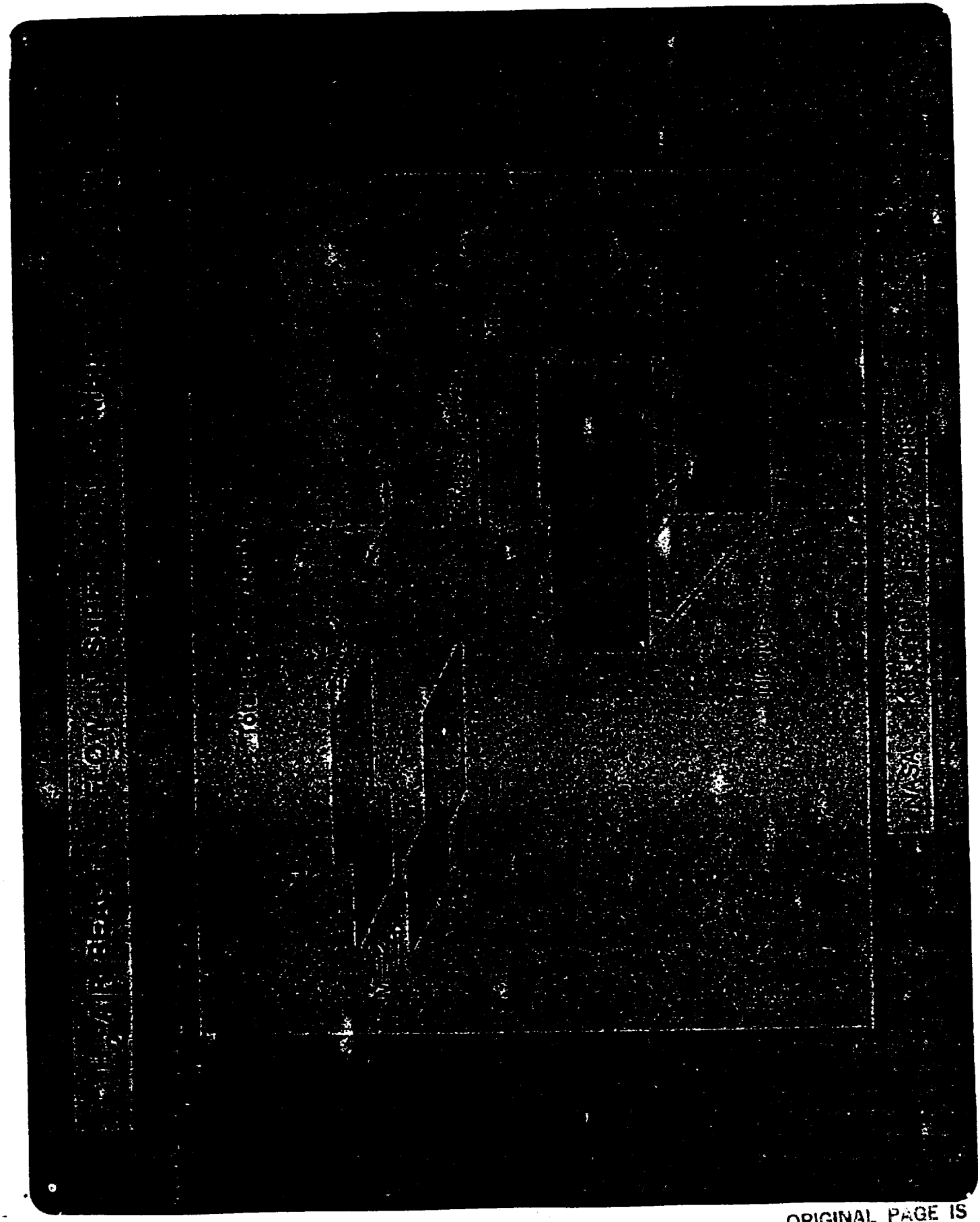
SUCCESSFUL "SPLICING" OF CODES CRUCIAL TO EFFICIENT APPLICATION TO COMBUSTOR ANALYSES.

SMALL SCALE TEST APPARATUS



Fuel injector region (Top view)





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CARS NONINTRUSIVE MEASUREMENTS

APPROACH

- CARS SYSTEM HAS BEEN DEVELOPED
  - DEMONSTRATED MEASUREMENT TECHNIQUES IN KNOWN ENVIRONMENT (CALIBRATION LIKE EXPERIMENTS)
  - DEMONSTRATED TECHNIQUES IN SUBSONIC DIFFUSION FLAME
  - COMPARED MEASUREMENTS WITH EXISTING CODES FOR SUBSONIC FLOW
- DEVELOPED SUPERSONIC MACH 2 COAXIAL DIFFUSION COMBUSTION EXPERIMENT
  - BURNER INSTALLED, CONTROLS BEING TESTED
  - HIGH SPEED LDV SYSTEM AND SEEDER BEING DEVELOPED AT VPI
- AXISYMMETRIC ELLIPTIC NS CODE BEING DEVELOPED TO MODEL FLOW

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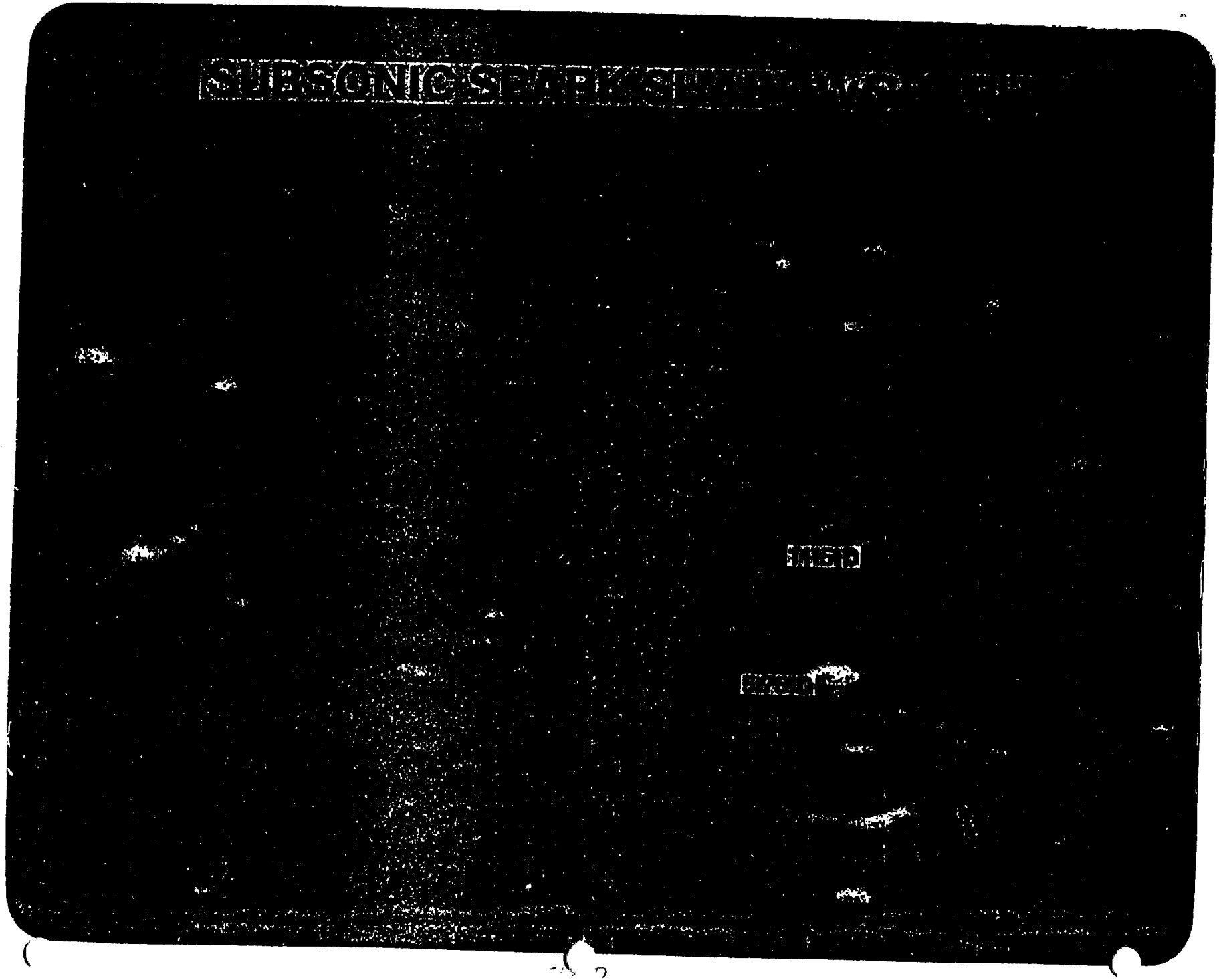
Space Administration



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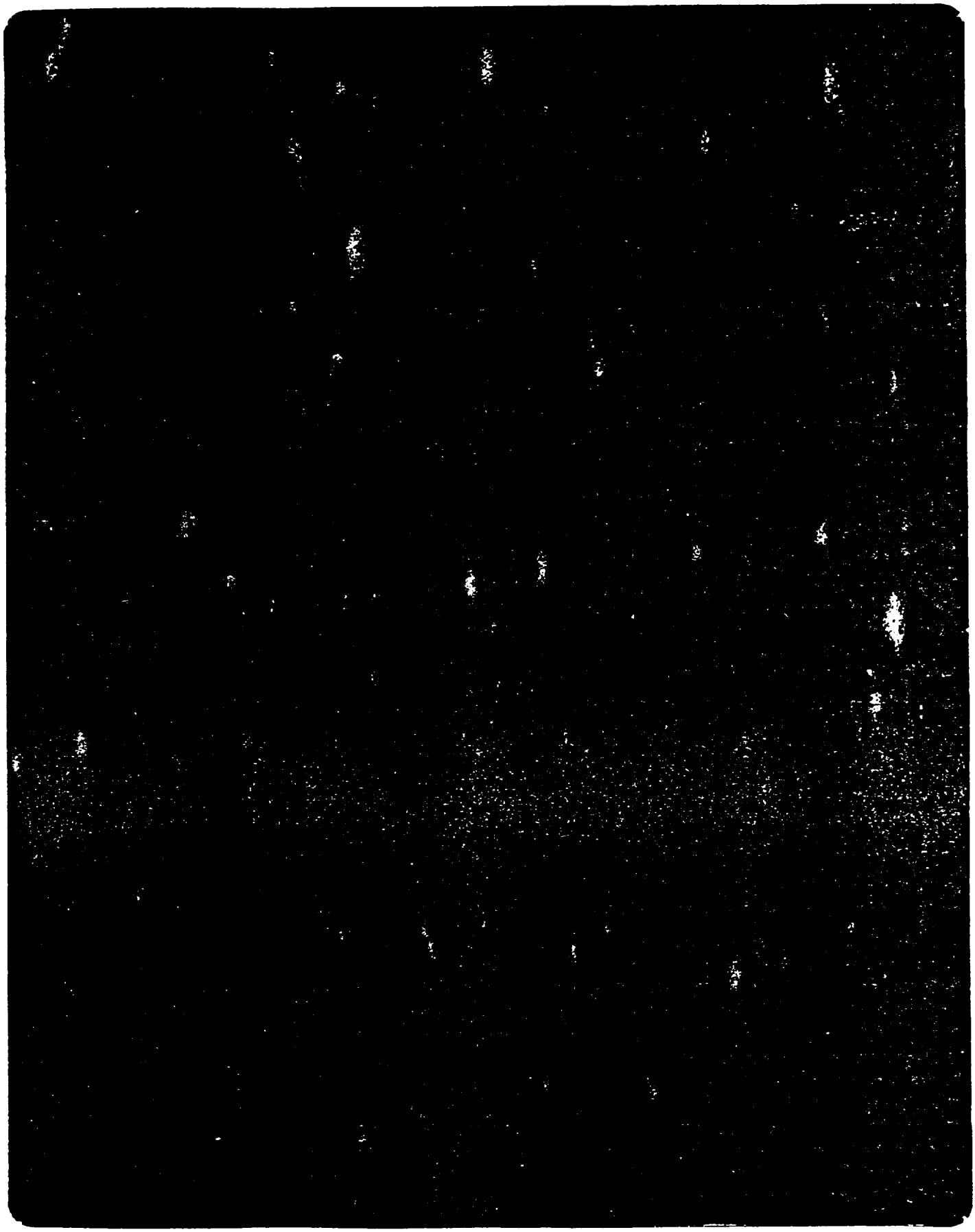

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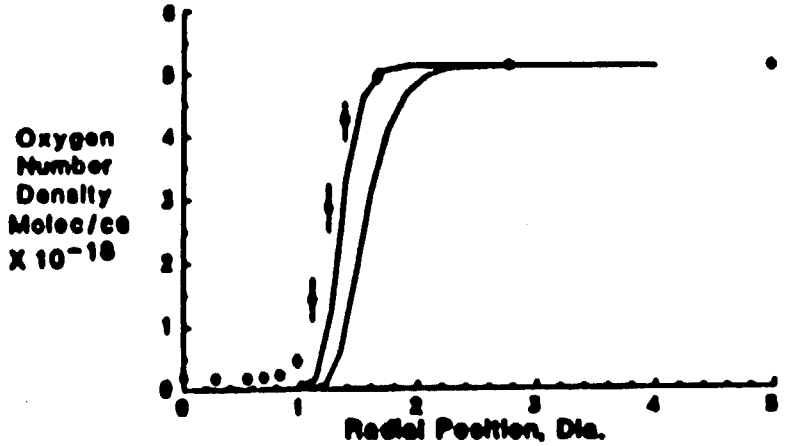
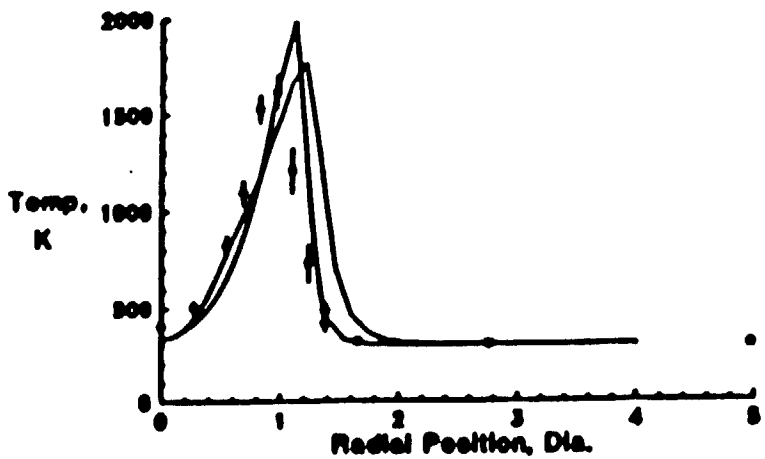
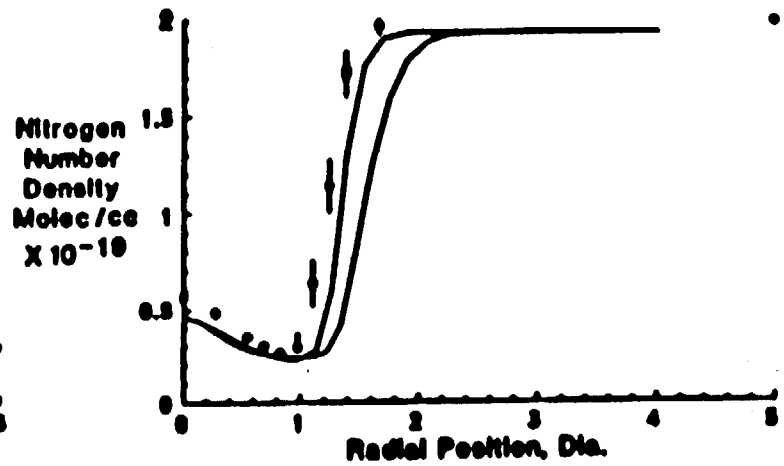
COMPARISON OF CALCULATIONS AND CARS DATA FOR SUBSONIC COAXIAL H_2-AIR BURNER

RADIAL PROFILE
5.5 Dia. downstream

- CARS average with 95% confidence interval
- Parabolized Navier–Stokes calculations
- TEACH code calculations







NASA LANGLEY RESEARCH CENTER UNCLASSIFIED

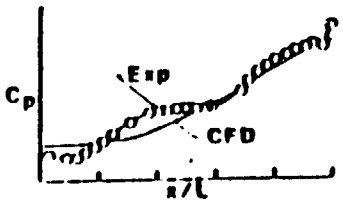
AERODYNAMIC CHARACTERISTICS OF STORES SEPARATING FROM CAVITIES

1986-1987

CAVITY FLOWFIELD
Full Navier-Stokes

Static pressure contours

Pressure distributions cavity floor

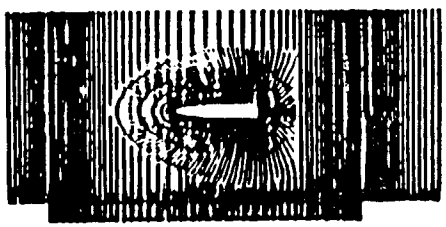


STORE FLOWFIELD
Thin-Layer Navier-Stokes

Static pressure contours

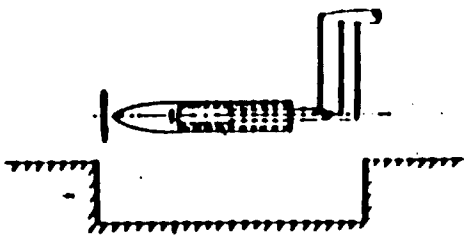
1987-1988

EMBEDDED FLOWFIELDS



- Flowfield
- Forces and Moments
- Pressures

EXPERIMENTAL MEASUREMENTS



- Forces and Moments
- Pressures

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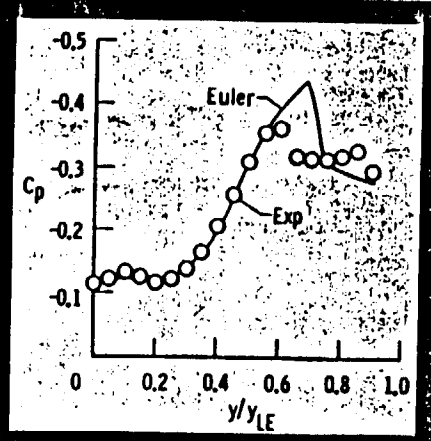
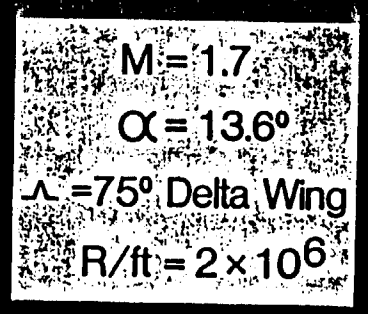
LEADING EDGE VORTEX FLOW - CFD RESULTS

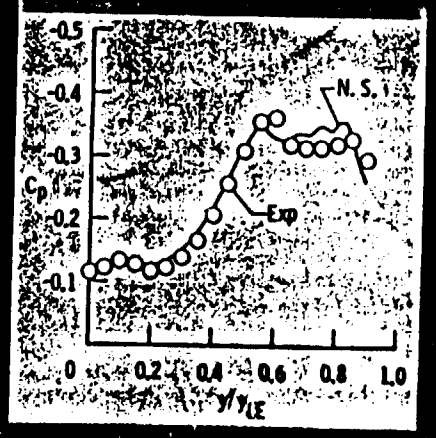
Euler



VAPOR SCREEN



Navier Stokes



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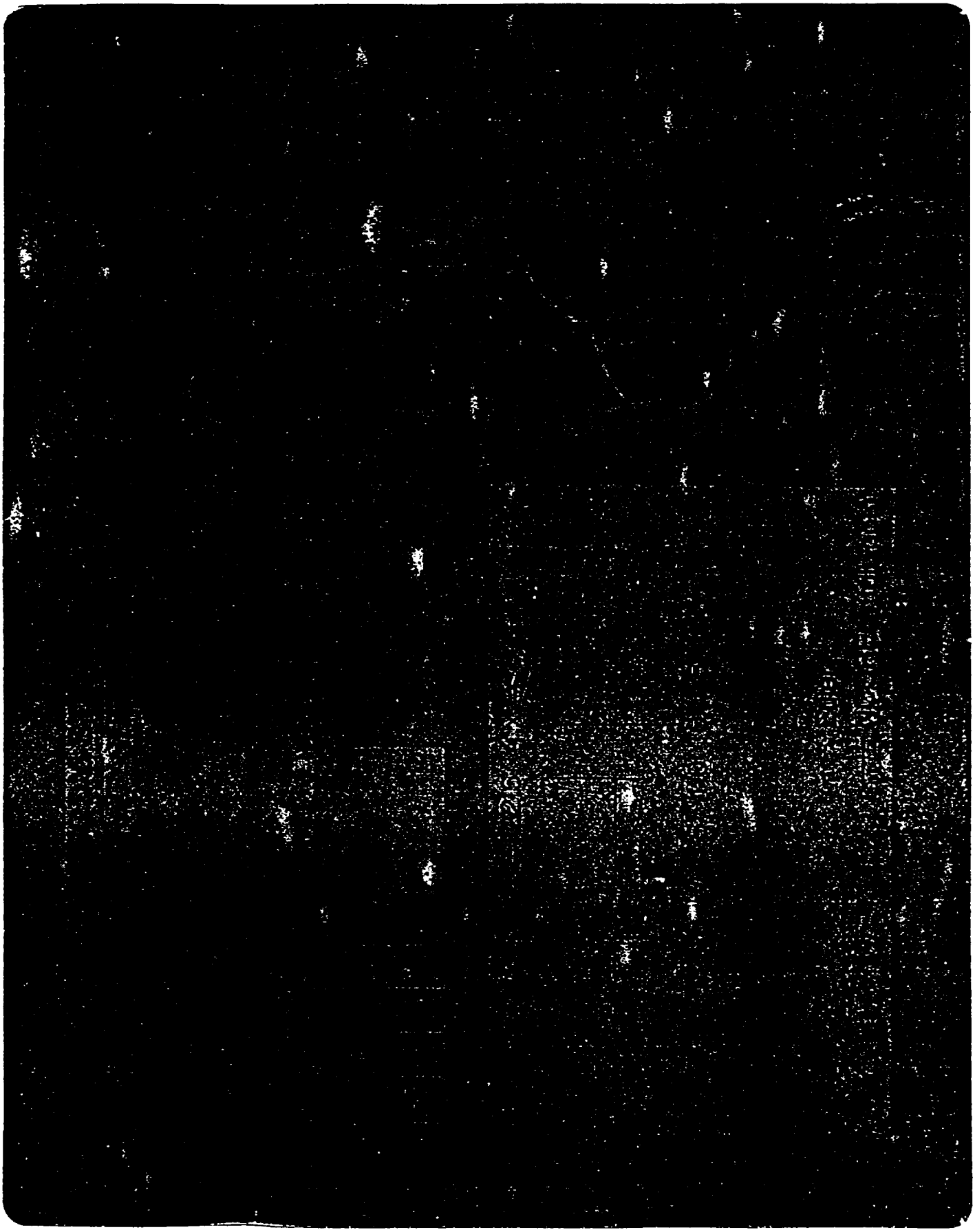

Space Administration

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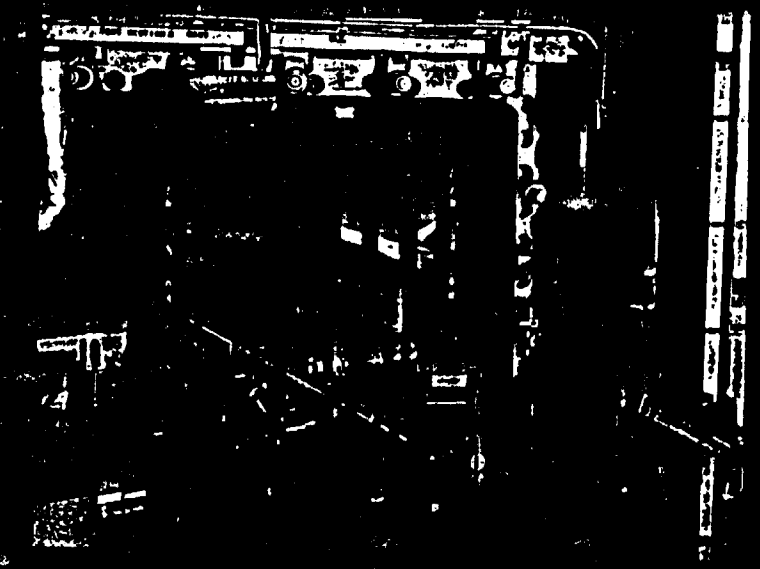
QUANTITATIVE FLOW FIELD MEASUREMENT TECHNIQUES

Automated conical probe
(Near-term)

Raman Doppler velocimeter
(Far-term)



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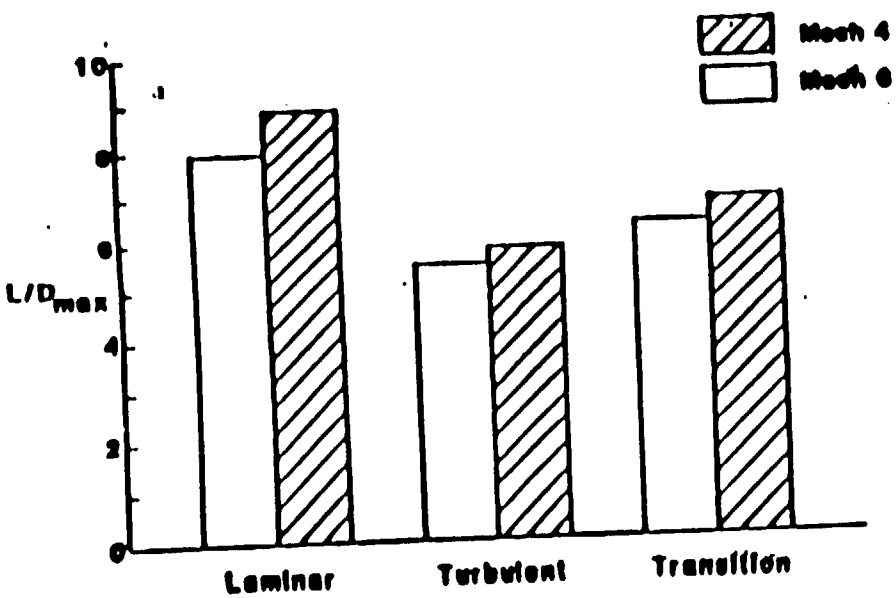
CODE VALIDATION STUDY
OPTIMIZED CONE-DERIVED WAVERIDER STUDY

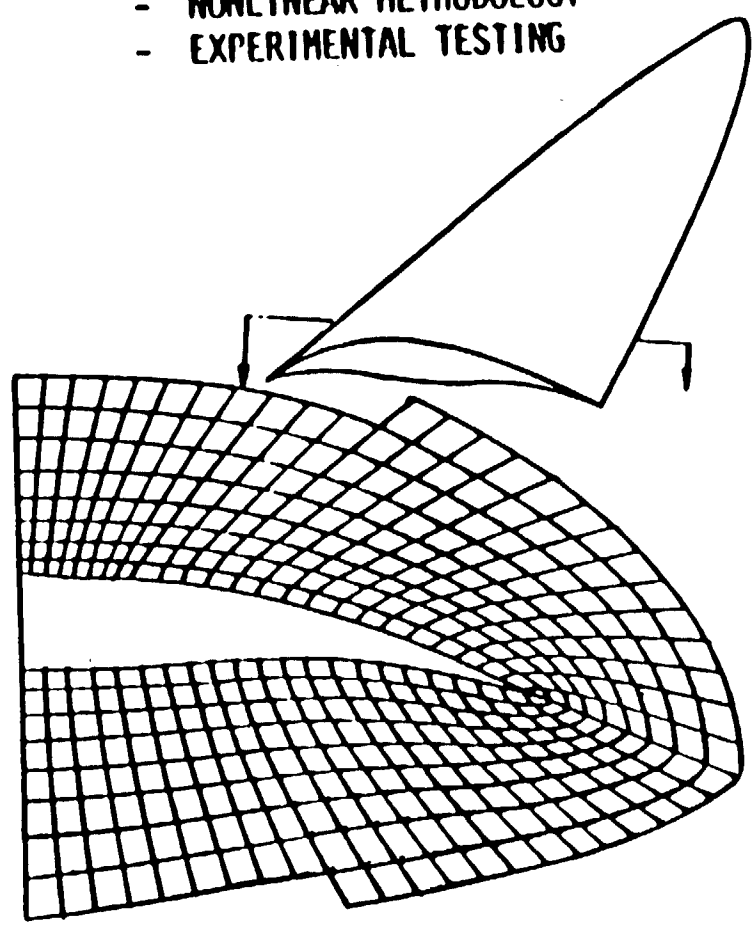
WAVERIDER OPTIMIZATION

- VISCOUS EFFECTS
- MACH NUMBER EFFECTS
- VOLUMETRIC TRADE-OFF
- AERODYNAMIC/PROPULSION INTEGRATION

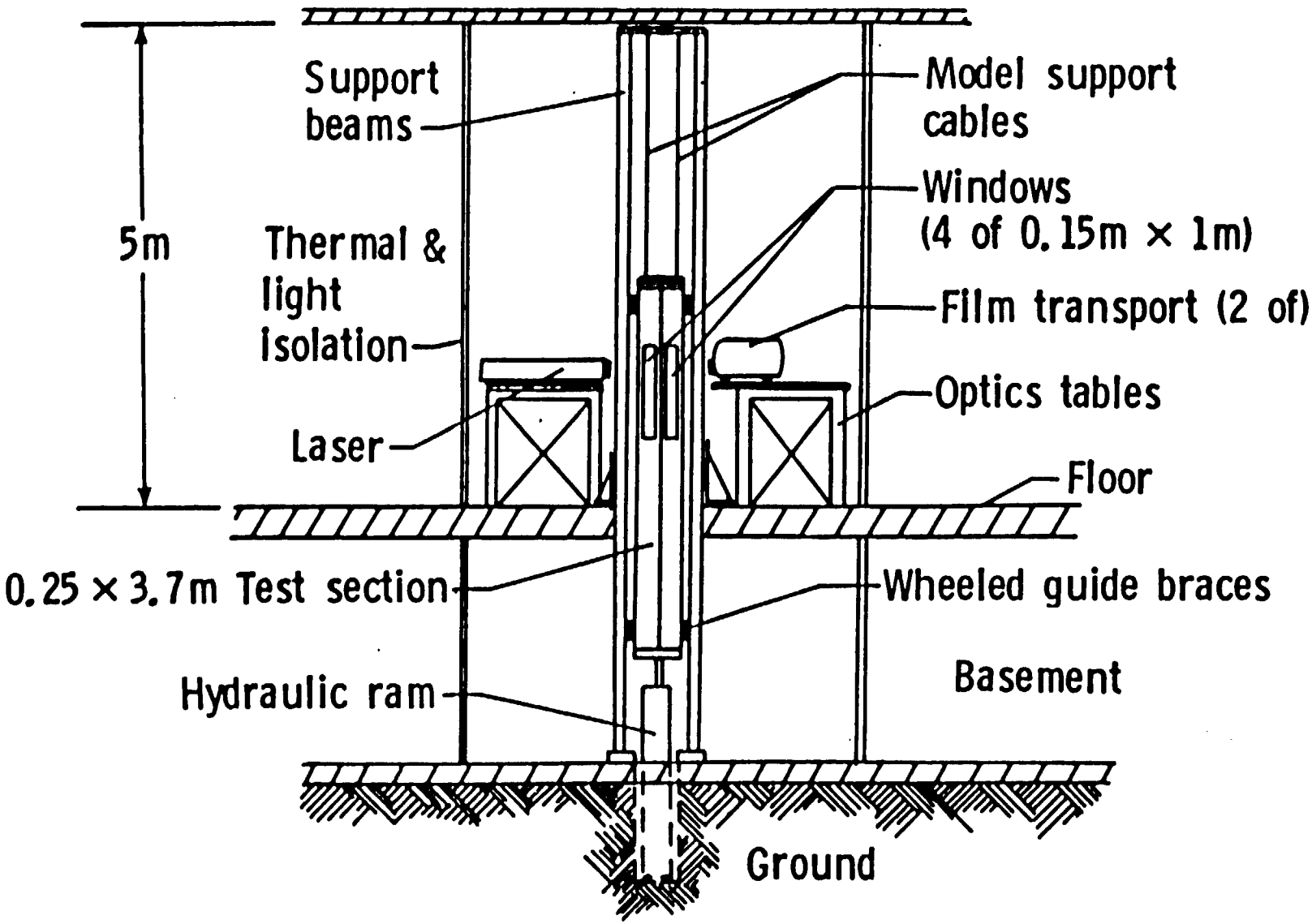


DESIGN VALIDATION

- NONLINEAR METHODOLOGY
- EXPERIMENTAL TESTING



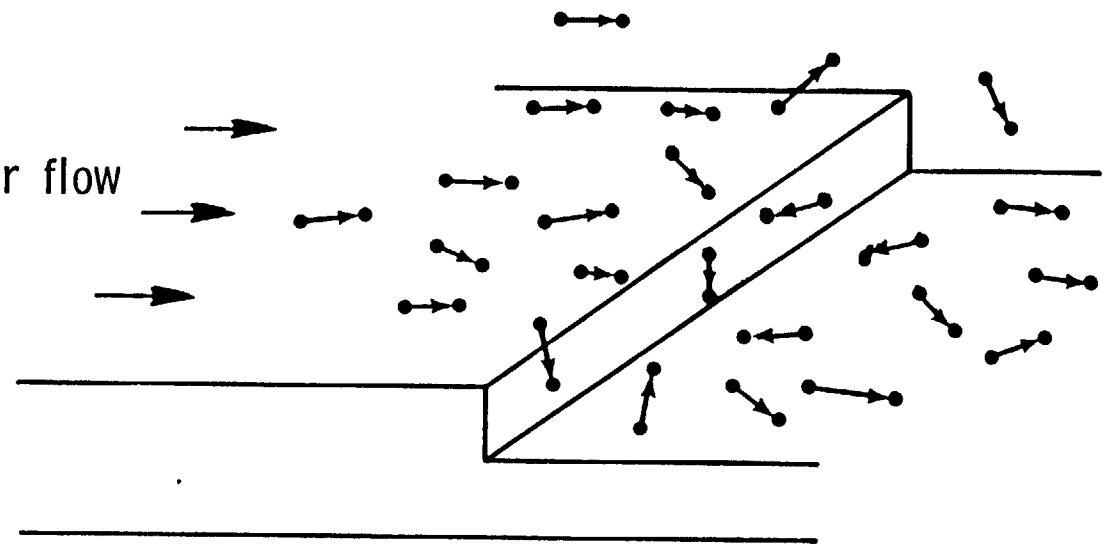
VERTICAL TRANSPORTED WATER TUNNEL



(Water Highlighted [illegible]) Hologram Movies
Time Varying

DETERMINING TIME VARYING VELOCITY FIELD WITH HCV

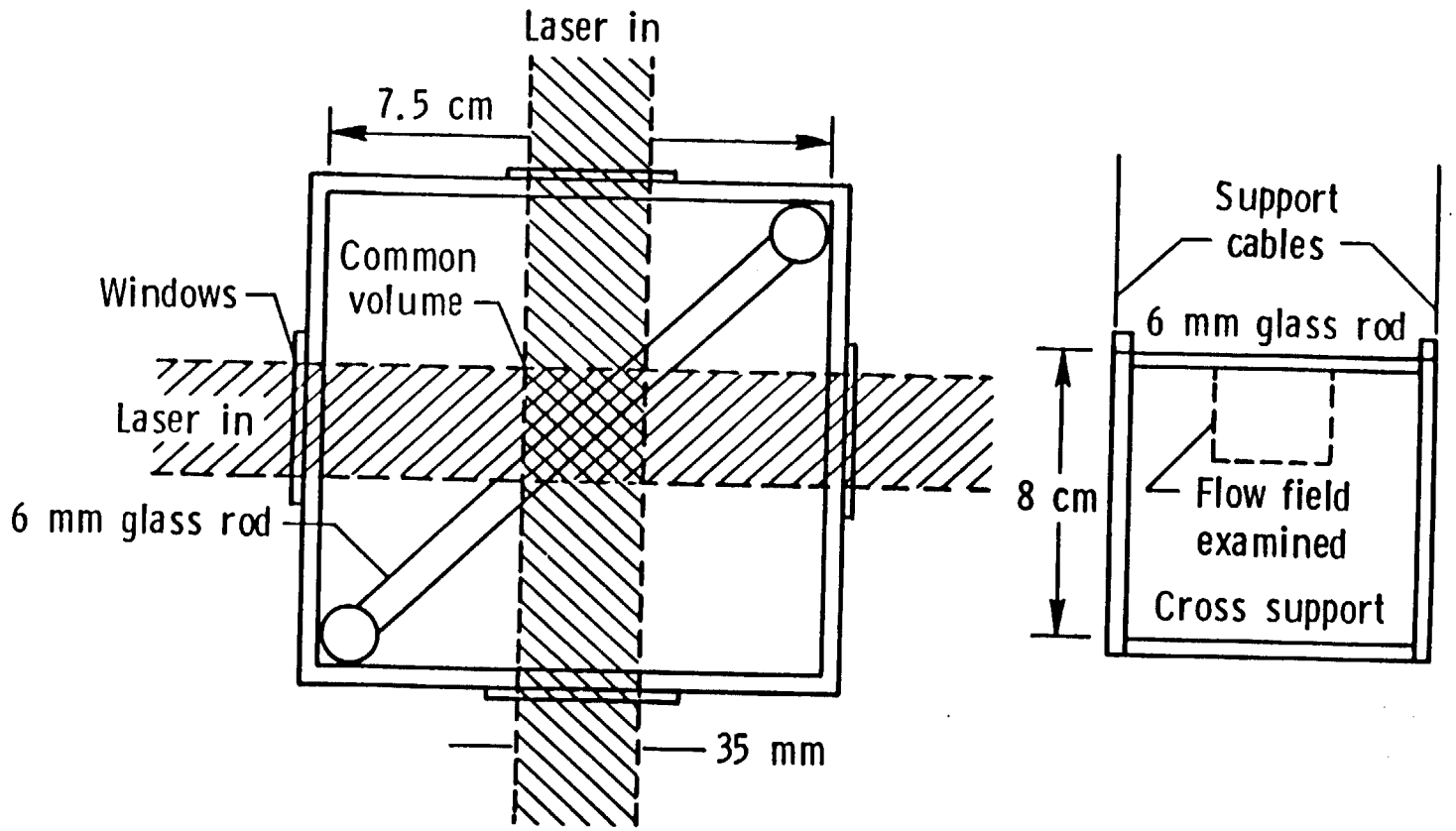
Low speed water flow
$U_\infty = 0.3\,m/s$



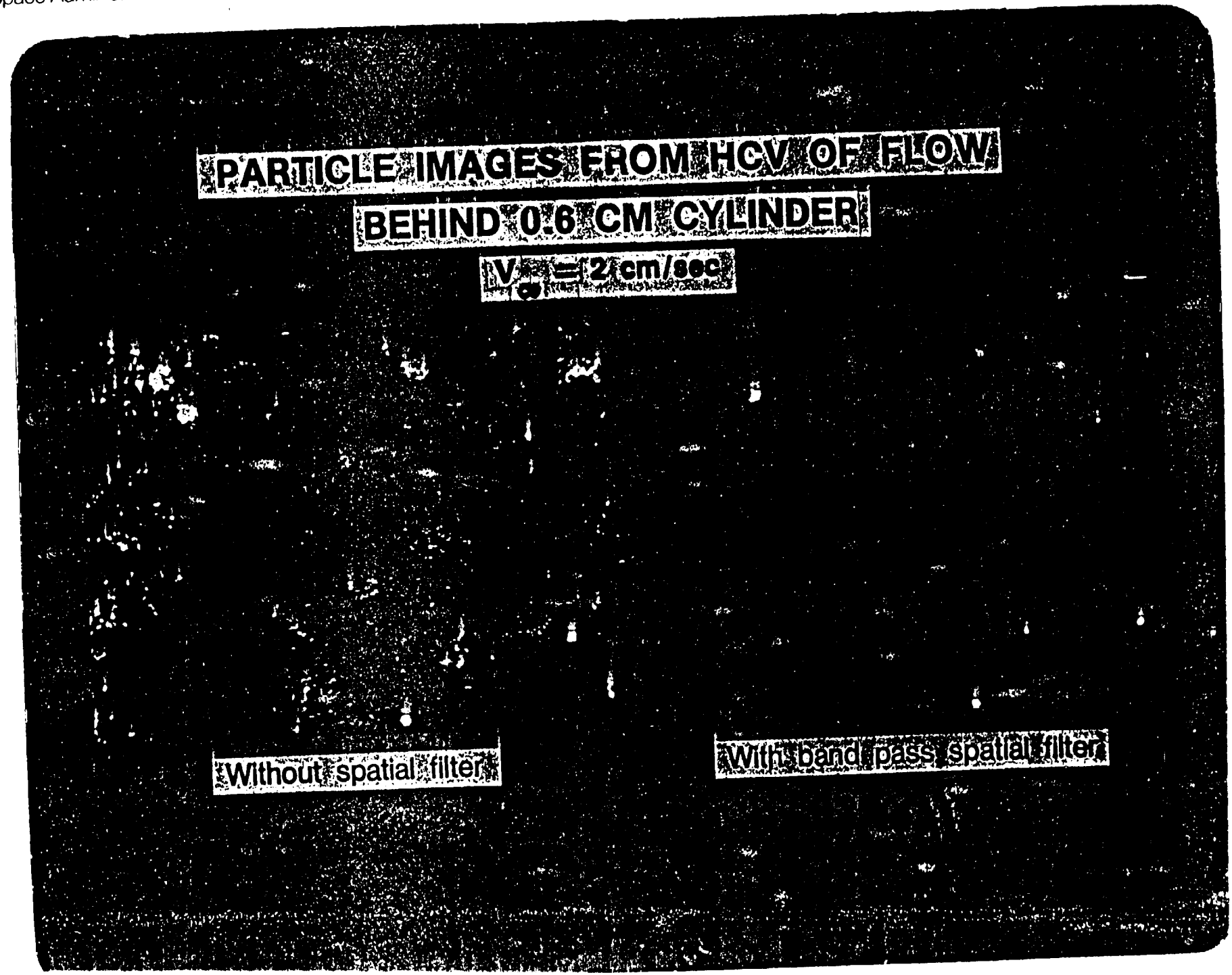
(Example-backward facing step)

- Make holographic movie of 3-d flow with tracer particles
- First in each sequential pair of frames → X, Y, Z at t
- Second in pair is located → ΔX, ΔY, ΔZ at Δt
- Data reduction for entire movie yields (in real time) $\bar{V}(X, Y, Z, t)$

DETAILS OF TUNNEL CROSS SECTION AND MODEL



LEONARD M. WEINSTEIN



OVERVIEW OF HYPERSONIC CFD CODE CALIBRATION STUDIES

CHARLES MILLER

EXPERIMENTAL AERODYNAMICS BRANCH

SPACE SYSTEMS DIVISION

LANGLEY RESEARCH CENTER

PRESENTED TO

NASA CFD VALIDATION WORKSHOP

AMES RESEARCH CENTER

JULY 14-16, 1987

N92-70932

OUTLINE

- BACKGROUND/PHILOSOPHY
  - DEFINITIONS OF CFD CODE VALIDATION
  - CLIMATE IN HYPERSONICS AT LANGLEY WHEN FIRST "DESIGNED" CFD CODE CALIBRATION STUDY INITIATED
  - METHODOLOGY (FROM EXPERIMENTALIST PERSPECTIVE)
  - SOME CONCERNS AT WORKING LEVEL
- EXPERIMENTAL RESOURCES
  - HYPERSONIC FACILITIES
  - MEASUREMENT TECHNIQUES
- CFD CODE CALIBRATION STUDIES
- RECOMMENDATIONS

BACKGROUND / PHILOSOPHY

DEFINITIONS OF CFD CODE VALIDATION

- AGENCY LEVEL - CFD VALIDATION AD HOC SUBCOMMITTEE OF AERONAUTICS ADVISORY COMMITTEE (AAC), 1987

  DETAILED SURFACE AND FLOWFIELD COMPARISONS WITH EXPERIMENTAL DATA TO VERIFY THE CODE'S ABILITY TO ACCURATELY MODEL THE CRITICAL PHYSICS OF THE FLOW. - - -

- WORKING LEVEL - MEMBERS OF AEROTHERMODYNAMICS BRANCH, SPACE SYSTEMS DIVISION, 1983*

  COOPERATIVE AGREEMENT BETWEEN EXPERIMENTALISTS AND COMPUTATIONALISTS; STUDY WORKED BEGINNING TO END BY BOTH PARTIES; MUTUALLY BENEFICIAL

* YEAR FIRST "DESIGNED" CFD CODE CALIBRATION STUDY INITIATED

BACKGROUND / PHILOSOPHY - Continued

1983 - CLIMATE IN HYPERSONICS AT LANGLEY

- CONTINUED DECLINE IN INTEREST IN HYPERSONICS
- LACK OF MAJOR HYPERSONIC PROGRAMS
- ERA OF HYPERSONICS BEING A "BAD WORD"

- RESOURCES
  - EXPERIMENTALISTS: LIMITED MANPOWER DUE TO LARGE MIGRATION FROM HYPERSONICS TO OTHER AREAS AND TO RETIREMENTS

AERODYNAMICS	4	Individuals
AEROTHERMODYNAMICS	2	
FLUID DYNAMICS	1	
FACILITY ENGINEERS	3	
	10	(Half in their 50's)

  - FACILITIES: BADLY NEGLECTED FOR OVER A DECADE
    - HYPERSONIC WIND TUNNELS:
      - 3 ACTIVE* (20-IN M = 6, 31-IN M = 10, HELIUM)
      - 4 STANDBY (M = 8 VDT, NITROGEN, HIGH-RE HELIUM, HE OJL)
      - 1 DEVELOPMENT (CF_4)
      - 1 DEDICATED TO LDV (M = 6 HIGH-RE)
    - HYPERSONIC / HYPERVELOCITY FACILITIES:
      - ARC DRIVEN SHOCK TUBE TERMINATED
      - EXPANSION TUBE / TUNNEL TERMINATED**

* ONLY ACTIVE HYPERSONIC WIND TUNNELS IN AGENCY

** TERMINATION OF AGENCY HYPERSONIC / HYPERVELOCITY TESTING

BACKGROUND / PHILOSOPHY - Continued

- EXPERIMENTALISTS ANXIOUS TO EXPAND HYPERSONIC ACTIVITIES
- COOPERATIVE AGREEMENT WITHIN AB / SSD ESTABLISHED
  - "HALIS ORBITER" FIRST CFD CODE CALIBRATION STUDY
- METHODOLOGY
  - DESIGN STUDY FOR COMPATIBILITY BETWEEN BOTH PARTIES, WITH EXPERIMENTALISTS PLACING EMPHASIS ON:
    - MODEL FIDELITY
    - DATA QUALITY
      - FLOW UNIFORMITY (AXIALLY, RADIALLY)
      - FREESTREAM TURBULENCE LEVEL
      - CONTAMINATION LEVEL
      - KNOWLEDGE OF FLOW CONDITIONS
        - VIBRATIONAL RELAXATION (EQ / NONEQ)
        - LIQUEFACTION
        - TRANSPORT PROPERTIES AT LOW TEMPERATURE
      - MODEL SUPPORT / PLACEMENT
        - ACCURATE ALPHA, BETA
        - SUPPORT INTERFERENCE EFFECTS
        - BLOCKAGE
  - EXAMINE EFFECTS OF MACH NUMBER, REYNOLDS NUMBER AND DENSITY RATIO (RATIO OF SPECIFIC HEATS) OVER WIDE RANGES
    - MULTIPLE FACILITY TESTING

BACKGROUND / PHILOSOPHY - Continued

PERCEIVED THREAT OF LOSING HYPERSONIC TESTING CAPABILITY

EXPERIMENTAL STUDIES IN 1983 - 1984
- BASIC RESEARCH
- PLANETARY AEROBRAKING / AEROCAPTURE
- SHUTTLE ORBITER (LIMITED TESTS)
- LIFTING BODY (MOU WITH AF)

VOICES IN BACKGROUND

BECAUSE WITHIN A DECADE COMPUTERS SHOULD BEGIN TO SUPPLANT WIND TUNNELS IN THE AERODYNAMIC DESIGN AND TESTING PROCESS, THE NATION NEEDS INTEGRATED PLANNING OF BOTH TO ACQUIRE THE MOST EFFECTIVE OVERALL CAPABILITY FOR THE 1980s AND BEYOND

DEAN R. CHAPMAN, ET. AL. - 1975

THE INFLUENCE OF COMPUTATIONAL FLUID DYNAMICS ON EXPERIMENTAL AEROSPACE FACILITIES - A FIFTEEN YEAR PROJECTION

NATIONAL RESEARCH COUNCIL - 1983

BACKGROUND / PHILOSOPHY - Continued

- METHODOLOGY - CONTINUED
  - PERFORM MEASUREMENTS BENEFICIAL TO CFD COMMUNITY WITH EMPHASIS ON ACCURACY; COMPARE PREDICTIONS TO MEASUREMENTS
    - MEASUREMENTS PRIORITIZED BY AB COMPUTATIONALISTS
      - ZEROTH ORDER
        - FLOWFIELD SURVEYS - NON-INTRUSIVE*
          - (3 COMPONENTS OF VELOCITY; 2 THERMODYNAMIC QUANTITIES)
        - FLOWFIELD SURVEYS - INTRUSIVE
          - PITOT PRESSURE
          - FLOW DIRECTION VIA PRESSURE MEASUREMENTS
          - TOTAL TEMPERATURE
          - MASS FLOW
      - FIRST ORDER
        - SURFACE HEAT TRANSFER RATE
        - SKIN FRICTION
      - SECOND ORDER
        - SURFACE PRESSURE

INCREASING COST

HELPFUL
- FORCES AND MOMENTS
- THERMAL MAPPINGS
- SURFACE STREAMLINE PATTERNS (OIL FLOW)
- SCHLIEREN PHOTOGRAPHS
- VAPOR SCREEN

* DEVELOPMENT OF HYPERSONIC NON-INTRUSIVE FLOW DIAGNOSTICS ESSENTIALLY TERMINATED IN MID 1970's

BACKGROUND / PHILOSOPHY - Continued

EXPERIMENTAL AERODYNAMICS BRANCH, SSD FORMED IN 1985

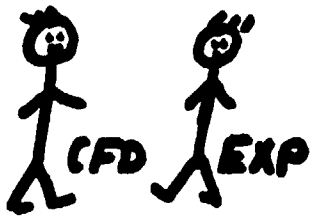
- REEXAMINED FLOW QUALITY IN LANGLEY HYPERSONIC WIND TUNNELS
- REEXAMINED TESTING / FLOW DIAGNOSTIC TECHNIQUES
- ADOPTED / ESTABLISHED FOLLOWING CFD CODE CALIBRATION STUDIES:
  - ELLIPTIC CONE
  - SHUTTLE ORBITER (FLIGHT AND WIND TUNNEL DATA)*
  - STRAIGHT - AND BENT - NOSE BICONICS*
  - HALIS ORBITER
  - AOTV DRAG BRAKE WITH PAYLOAD
  - FAMILY OF BLUNT SPHERE CONES, SHARP AND ROUNDED CORNERS
  - HYPERSONIC NOZZLES
  - AEROASSISTED FLIGHT EXPERIMENT VEHICLE
  - WINGED CONE (NASP ACCELERATOR CONCEPT)

* STUDIES ESSENTIALLY COMPLETED AT TIME EAB FORMED

CARTOON USED AT AB/SSD MEETING, 1985

A CONCERN
MAINTAINING INTEREST OF CFD RESEARCHER

TIME →



ORIGINATE STUDY (E.G., ORBITER)
ESTABLISH GOALS
AND RESPONSIBILITIES

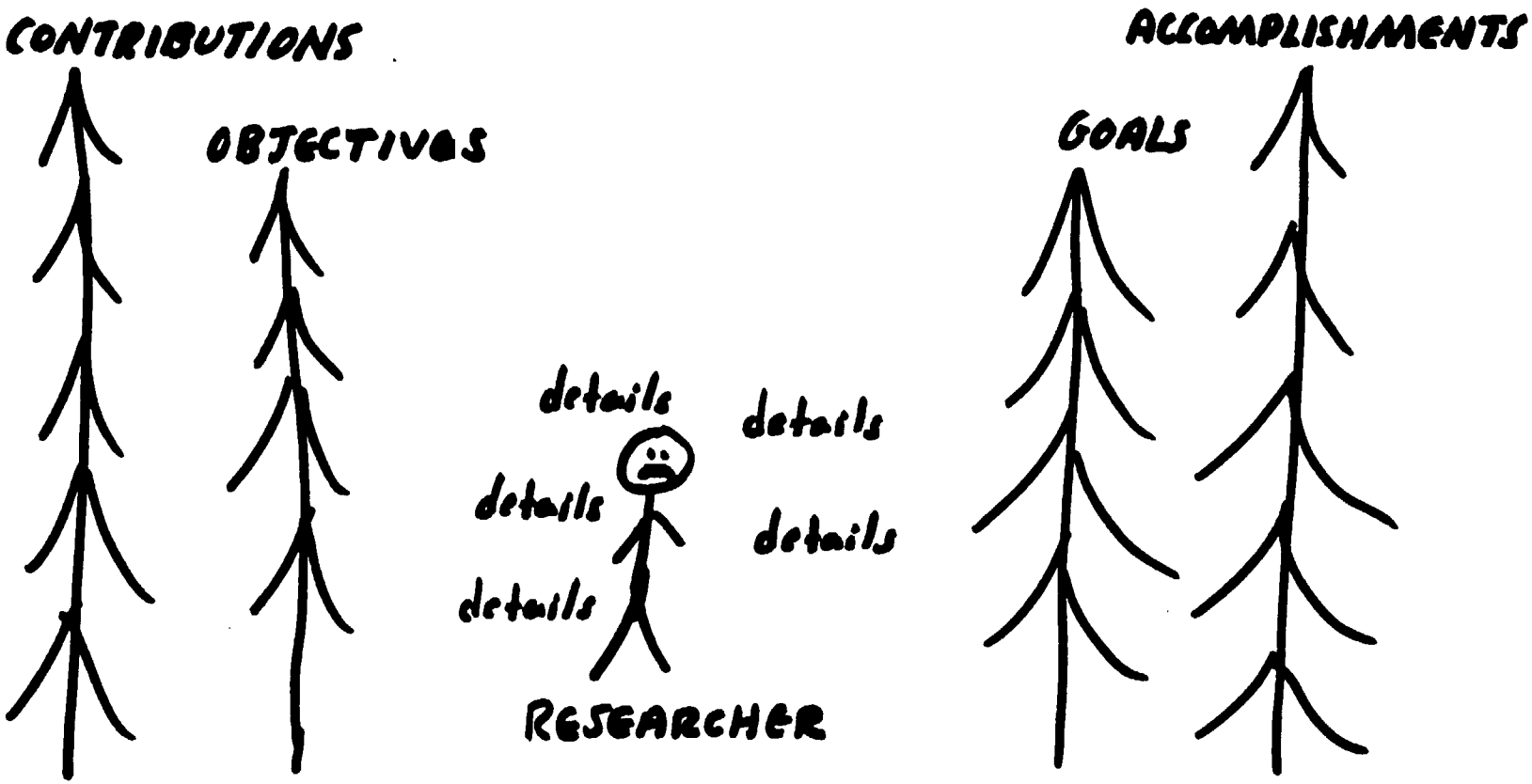
DESIGN – ENGINEERING – DRAWINGS – CONTRACT
FAB – PROCUREMENT – SAFETY – QA
TUNNEL SCHEDULES – TESTS
DATA REDUCTION – ANALYSIS

AFE

NASP

CARTOON USED AT AB/SSD MEETING, 1985

A CONCERN
"CAN'T SEE FOREST BECAUSE OF TREES"



A CONCERN

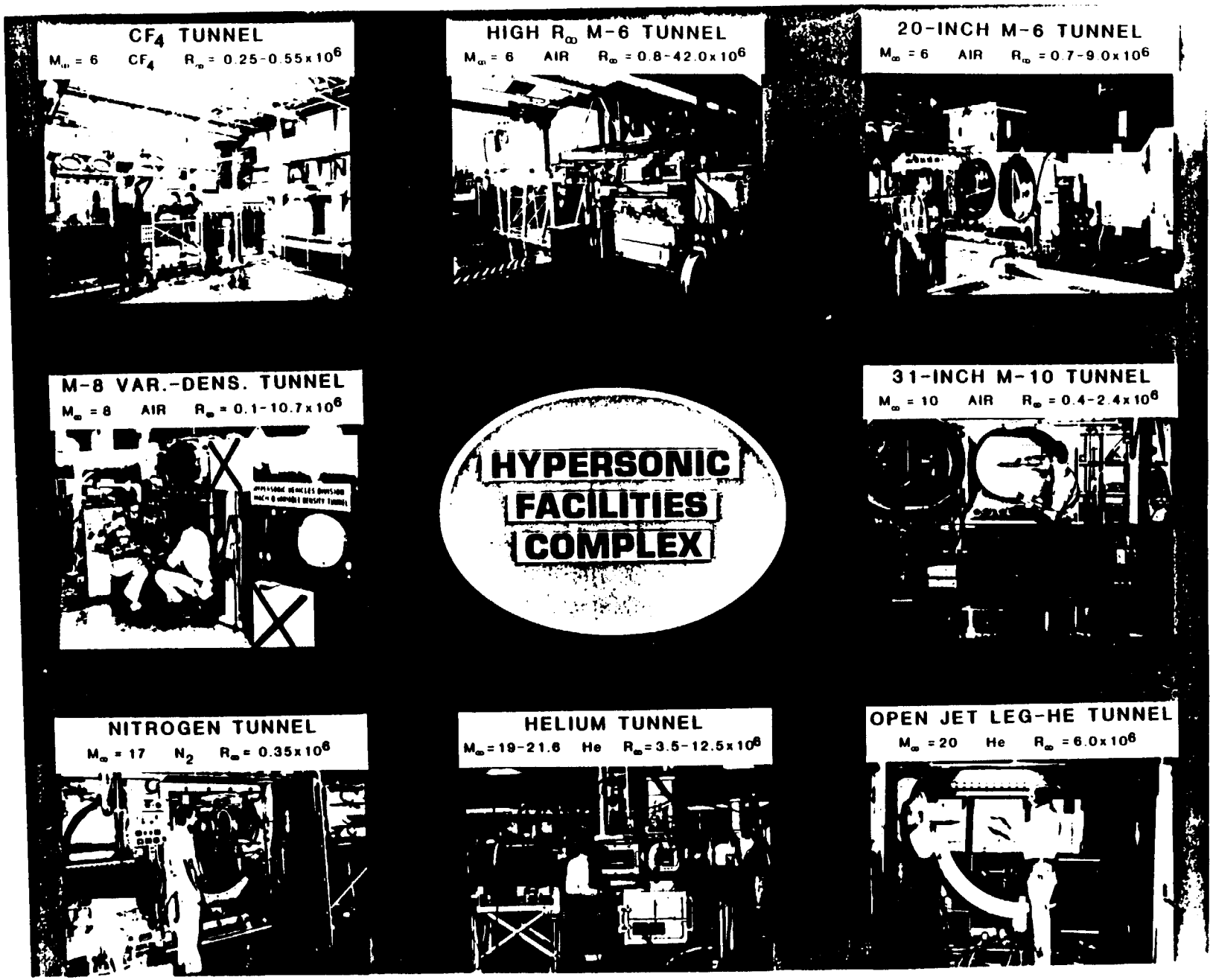
DIFFERENT WAVELENGTHS ON ACCURACY OF DATA

p TO WITHIN .1 %
$\dot{q}$ TO WITHIN .2 %

p TO WITHIN 3 %
$\dot{q}$ TO WITHIN 8 %

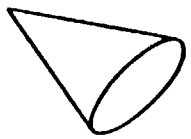
MODEL FIDELITY (.002 - .003")
QA CREDIBILITY
KNOWLEDGE OF FLOW CONDITIONS
ACCURACY OF ANGLE OF ATTACK AND SIDESLIP
FLOW QUALITY - THOSE D--- AXISYMMETRIC "CONTOURED" NOZZLES
FLOW CONTAMINATION
1986 DATA WITH 1960 FACILITIES AND INSTRUMENTATION

NASA
L-85-340


CF4 TUNNEL
M∞ = 6 CF4 R∞ = 0.25-0.55x10^6
HIGH R∞ M-6 TUNNEL
M∞ = 6 AIR R∞ = 0.8-42.0x10^6
20-INCH M-6 TUNNEL
M∞ = 6 AIR R∞ = 0.7-9.0x10^6
M-8 VAR.-DENS. TUNNEL
M∞ = 8 AIR R∞ = 0.1-10.7x10^6
HYPERSONIC
FACILITIES
COMPLEX
31-INCH M-10 TUNNEL
M∞ = 10 AIR R∞ = 0.4-2.4x10^6
NITROGEN TUNNEL
M∞ = 17 N2 R∞ = 0.35x10^6
HELIUM TUNNEL
M∞ = 19-21.6 He R∞ = 3.5-12.5x10^6
OPEN JET LEG-HE TUNNEL
M∞ = 20 He R∞ = 6.0x10^6

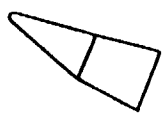
HYPERSONIC FACILITIES COMPLEX

FACILITY	TEST GAS	M_∞	$R_\infty \times 10^{-6}$ PER FT.	γ_∞	ρ_2/ρ_∞	TEST CORE SIZE, IN.	STATUS 4/87
HYP. CF_4	CF_4	6	0.2-0.7	1.22	12	14	ACTIVE
20-INCH MACH-6	AIR	6	0.6-9	1.40	5.3	14 X 14	ACTIVE
M-8 VAR. DEN.	AIR	8	0.1-10	1.40	5.6	7-16	STANDBY
31-INCH M-10	AIR	10	0.5-2	1.40	6	12 X 12	ACTIVE
HYP. NITROGEN	N_2	17	0.2-0.8	1.40	6.6	6-8	DEVELOP.
22-INCH HELIUM	HE	18-22	2.5-20	1.67	4	8-10	ACTIVE
OPEN JET LEG/ HYP. HELIUM	HE	20	~3	1.67	4	10	DEVELOP.
M-20, HIGH RN HELIUM	HE	16-19	0.8-29	1.67	4	20	STANDBY
M-6 HIGH RN	AIR	6	2-50	1.40	5.3	4-8	ACTIVE



ELLIPTIC CONE

NASP FOREBODY



BENT BICONIC

EXPERIMENTAL DATA

$6 < M < 22$	Global Measurements
$3 \times 10^5 < R < 12 \times 10^6$ /ft	Surface Quantities
$1.1 < \gamma < 1.7$	Flowfield (Intrusive)

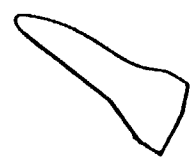
LANGLEY AEROTHERMODYNAMIC CODE VERIFICATION STUDIES

COMPUTATIONAL FLUID DYNAMICS

HALIS	SOFIA	VSL
3DAABL	LAURA	PNS

AFE

AOTV



"HALIS" ORBITER

ELLIPTIC CONE

This study was initiated to establish a comprehensive data base for a simple shape, which provides a complex flowfield, that would serve as a benchmark for code verification. The model is a 2 to 1 elliptic cone, for which the cone half angle along the minor axis of the elliptical cross-section is 10°, that is 11 inches long. Two interchangeable nose tips were fabricated for the model; one is sharp and the other is spherical with a 0.05-in. radius. An uninstrumented model and a model having surface pressure orifices and thin-film heat transfer gages have been built.

Tests have been performed in the 20-Inch Mach 6 Tunnel over an angle of attack range from 0° to 20° in the plane of minor axis and from 0° to 15° in the plane of the major axis; the freestream unit Reynolds number was varied from 1.5 to 7 million per ft. The program is complemented with the measurement of surface streamline patterns via the oil flow technique and by schlieren photographs of the shock shape.

Pitot pressure surveys within the shock layer have been measured at 4 longitudinal stations along the major and minor axes for 13° angle of attack. At this time, tests are being performed in the Mach 6 tunnel to obtain pitot pressure and flow angularity profiles within the shock layer simultaneously using a single probe. Future plans call for the measurement of total temperature surveys at Mach 6 in air and similar testing in the CF_4, Mach 10, and helium tunnels.

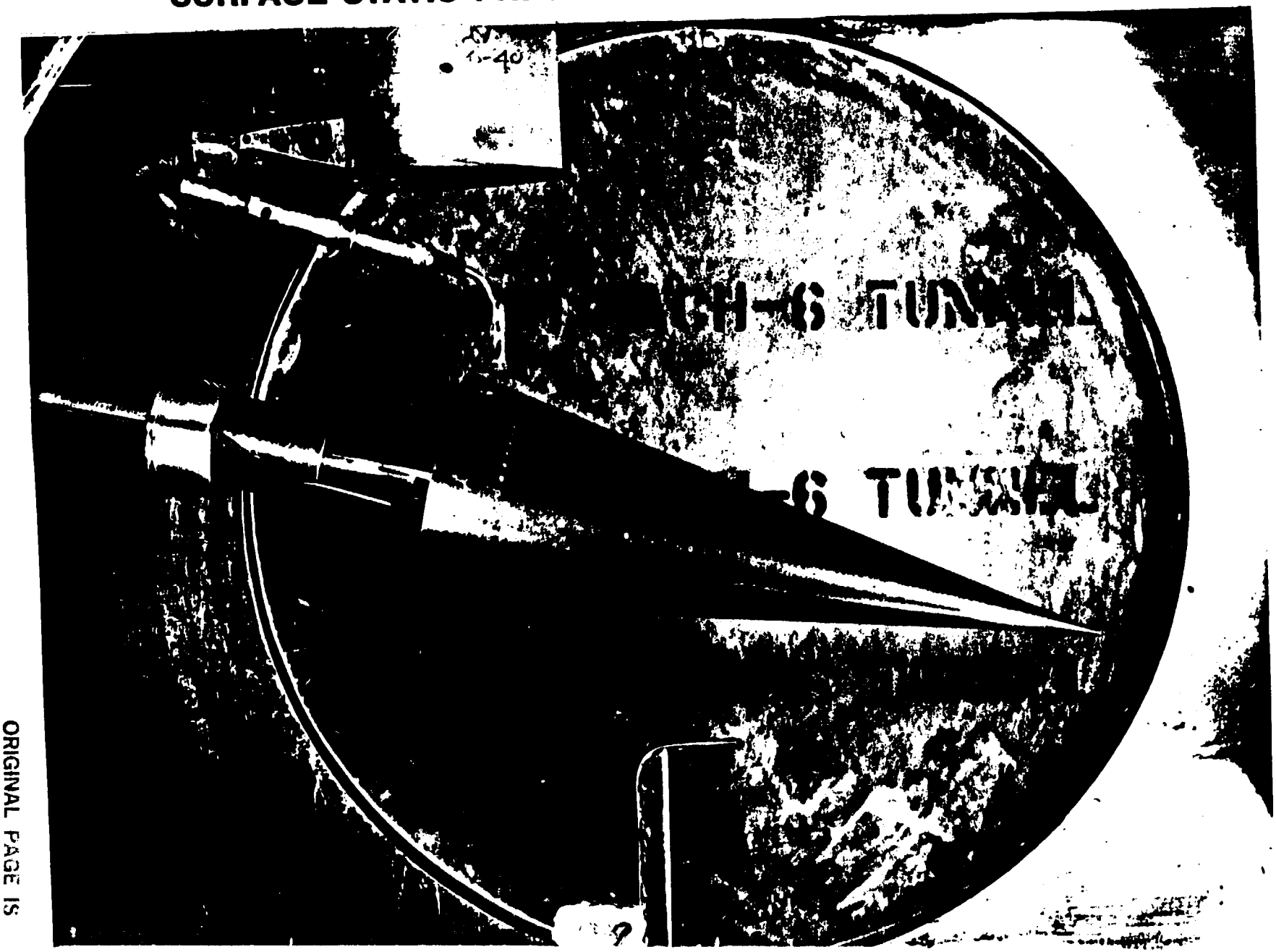
Reference:

1. Ashby, George C., Jr., "Flow Field and Surface Measurements on a 2:1 Elliptical Cone at Hypersonic Speeds," presented at the Third NASP Technology Symposium, Moffett Field, California, Paper No. 7, June 2-4, 1987.

CODE VERIFICATION RESEARCH

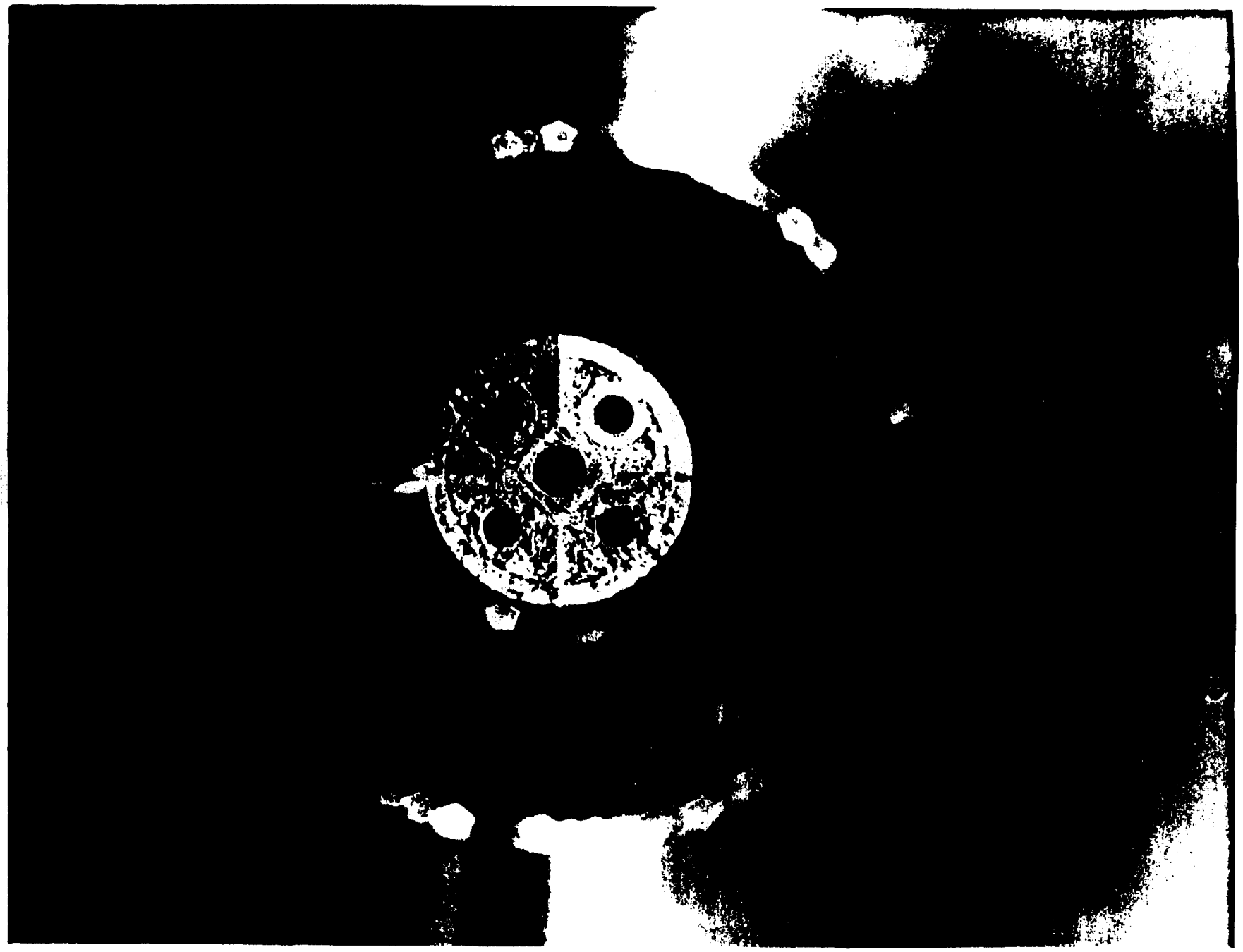
2:1 ELLIPTIC CONE

SURFACE STATIC PRESSURES AND FIELD PITOT SURVEY



ORIGINAL PAGE IS
OF POOR QUALITY

FRONT VIEW OF PROBE TIP – 0.058 INCH DIAM.



BICONICS

A program was initiated at the Langley Research Center to establish a comprehensive hypersonic data base for an aeroassisted vehicle proposed initially for a Mars sample return mission and later as a generic planetary vehicle. This vehicle is a 13°/7° biconic with the fore-cone section bent 7° upward to provide self-trim capability at an angle of attack of 20°. The Langley tests on this configuration began with the measurement of pressure distributions, surface oil-flow patterns, and shock shapes on 2.9 percent scale model in the 20-Inch Mach 6 Tunnel. Also tested was a straight biconic with the same nose radius, base radius, and half angles. The study was expanded to include pressure distributions on these two models in the 31-Inch Mach 10 Tunnel and the Hypersonic CF_4 Tunnel. These three wind tunnels, which are members of the Langley Hypersonic Facilities Complex, provided a range of freestream Mach number (6 and 10 in air), freestream unit Reynolds number (2×10^6/m to 27×10^6/m at Mach 6 in air), and normal shock density ratio (5.2 for Mach 6 air and 12 for Mach 6 CF_4). Tests in the CF_4 Tunnel were of particular interest since they simulated the low gamma (ratio of specific heats) aspect of the flow about a reentry vehicle which occurs because of real-gas effects. Following the pressure tests, forces and moments were measured on 2.9 percent scale models in all three wind tunnels; the angle of attack was varied from -10° to 40° for these tests, which also included the study of flap effectiveness at Mach 10. The last phase in the establishment of the data base for these two biconics was the measurement of heating distributions.

The Langley Expansion Tube, an impulse-type facility with a run time of only 250 microseconds, supplied the first heating distributions on the straight and bent-nose biconics. The models were smaller (1.9 percent scale) than those tested previously in the wind tunnels of the Hypersonic Facilities Complex, and only longitudinal heating distributions were measured along two rays (most windward and most leeward). At the time of the tests in the expansion tube, larger (2.9 percent scale) heat-transfer models containing twice as many heat-transfer gages were being fabricated for the conventional-type hypersonic wind tunnels. Because of the relatively long time required for the fabrication and instrumentation of these models, the smaller models designed and tested in the expansion tube were tested first in the 31-Inch Mach 10 Tunnel. These tests in the Mach 10 tunnel represented a milestone at Langley since they were the first to use a large number of thin-film resistance gages to measure heating rates on a model in a conventional wind tunnel.

References:

1. Miller, C. G. and Gnoffo, P. A., "Pressure Distributions and Shock Shapes for 12.84°/7° On-Axis and Bent-Nose Biconics in Air at Mach 6," NASA TM-83222, December 1981.

2. Miller, C. G. and Gnoffo, P. A., "An Experimental Investigation of Hypersonic Flow Over Biconics at Incidence and Comparison to Prediction," AIAA Paper 82-1382, August 1982.

3. Miller, C. G., Blackstock, T. A., Helms, V. T., and Midden, R. E., "An Experimental Investigation of Control Surface Effectiveness and Real-Gas Simulation for Biconics," AIAA Paper 83-0213, January 1983.

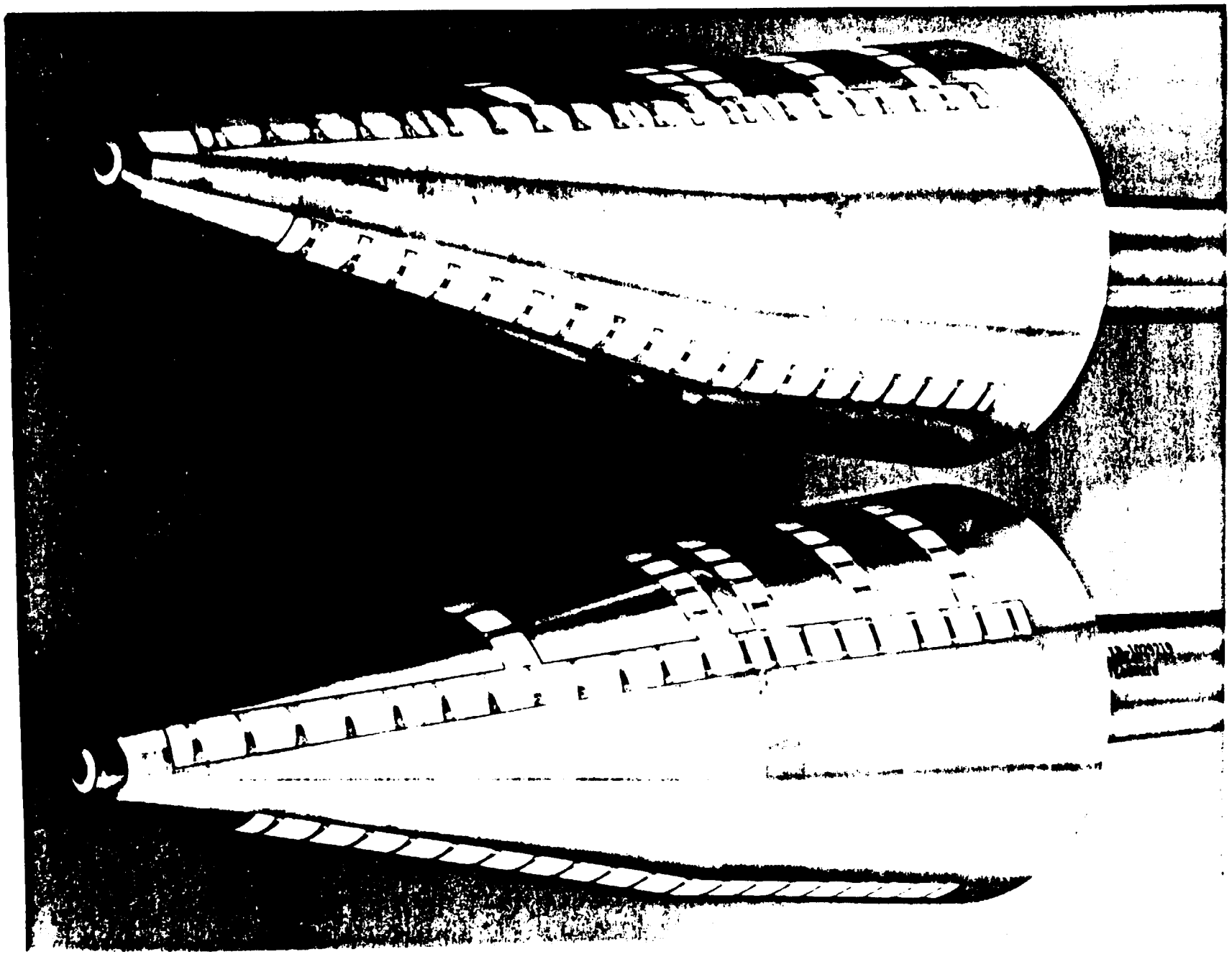
4. Miller, C. G., Gnoffo, P. A., and Micol, J. R., "Laminar Heat Transfer Distributions on Biconics at Incidence in Hypersonic-Hypervelocity Flows," NASA TP 2213, 1984.

5. Miller, C. G., Gnoffo, P. A., and Wilder, S. E., "Experimental Heating Distributions for Biconics at Incidence in Mach 10 Air and Comparison to Prediction," AIAA Paper 84-2119, August 1984.

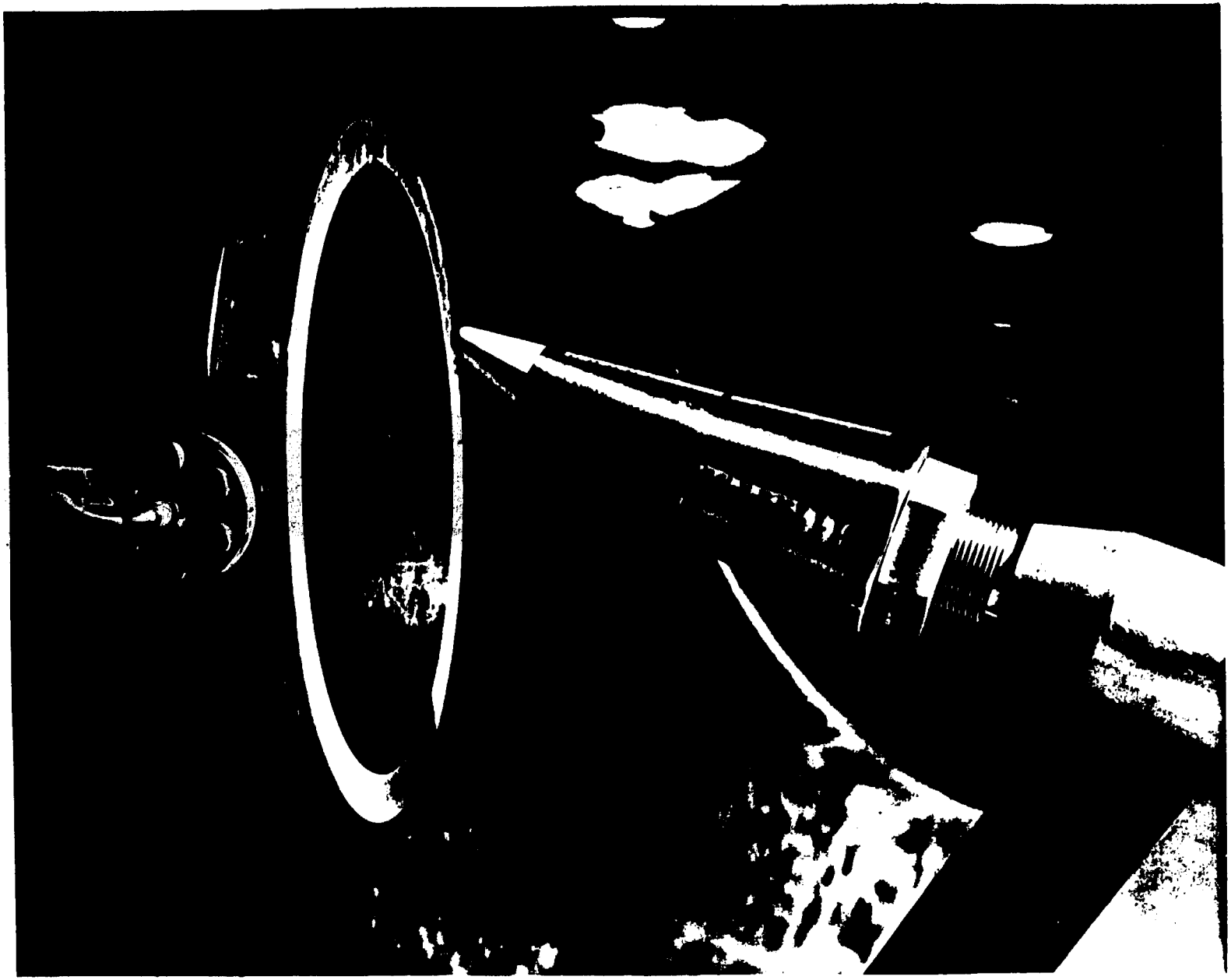
6. Miller, C. G., "Experimental and Predicted Heating Distributions for Biconics at Incidence in Air at Mach 10," NASA TP 2334, November 1984.

7. Miller, C. G., Wilder, S. E., Gnoffo, P. A., and Wright, S. E., "Measured and Predicted Vortex-Induced Leeward Heating on A Biconic at Mach 6 and 10," AIAA Paper 85-1061, June 1985.

BICONIC MODELS WITH THIN [illegible] HEAT TRANSFER GAGES

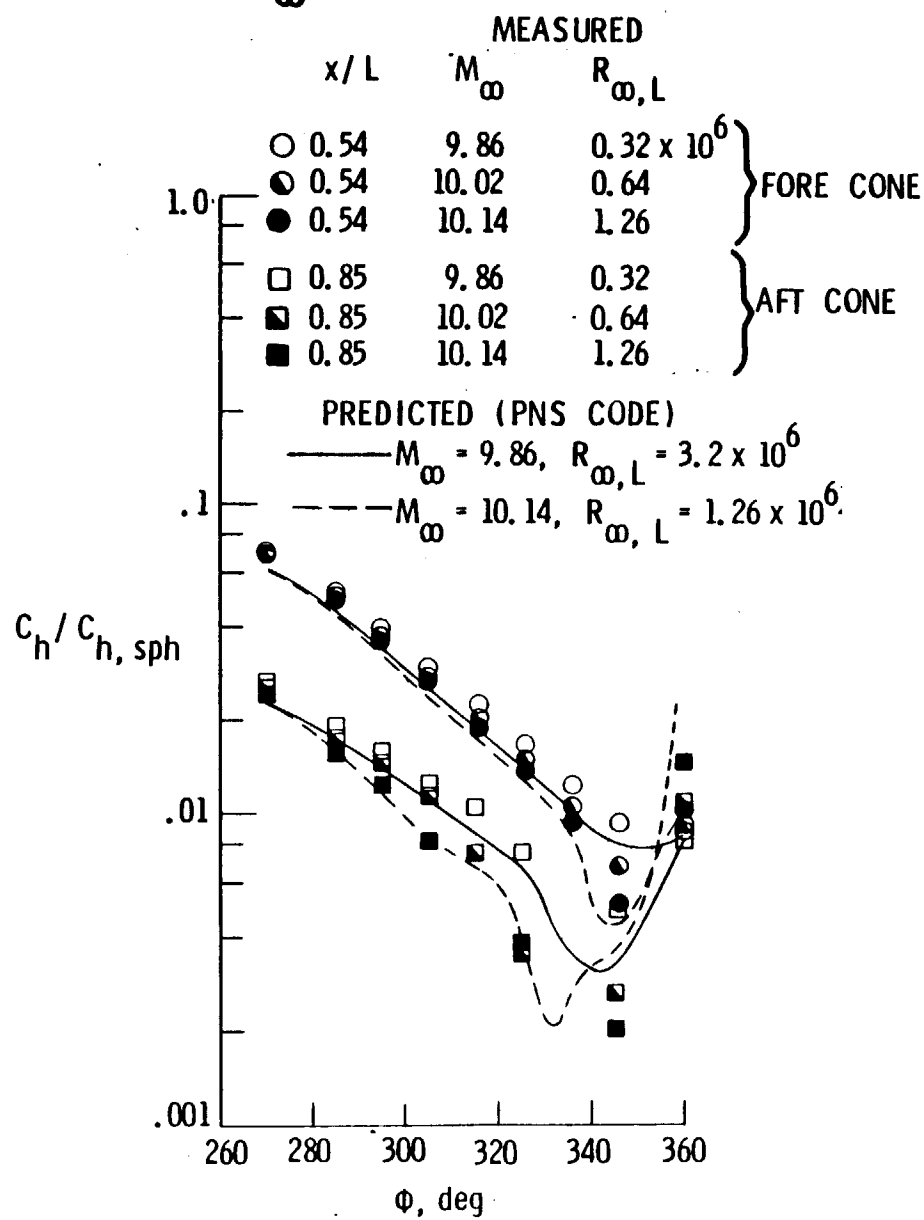


BENT BICONIC MODEL IN EXPANSION TUBE TEST SECTION



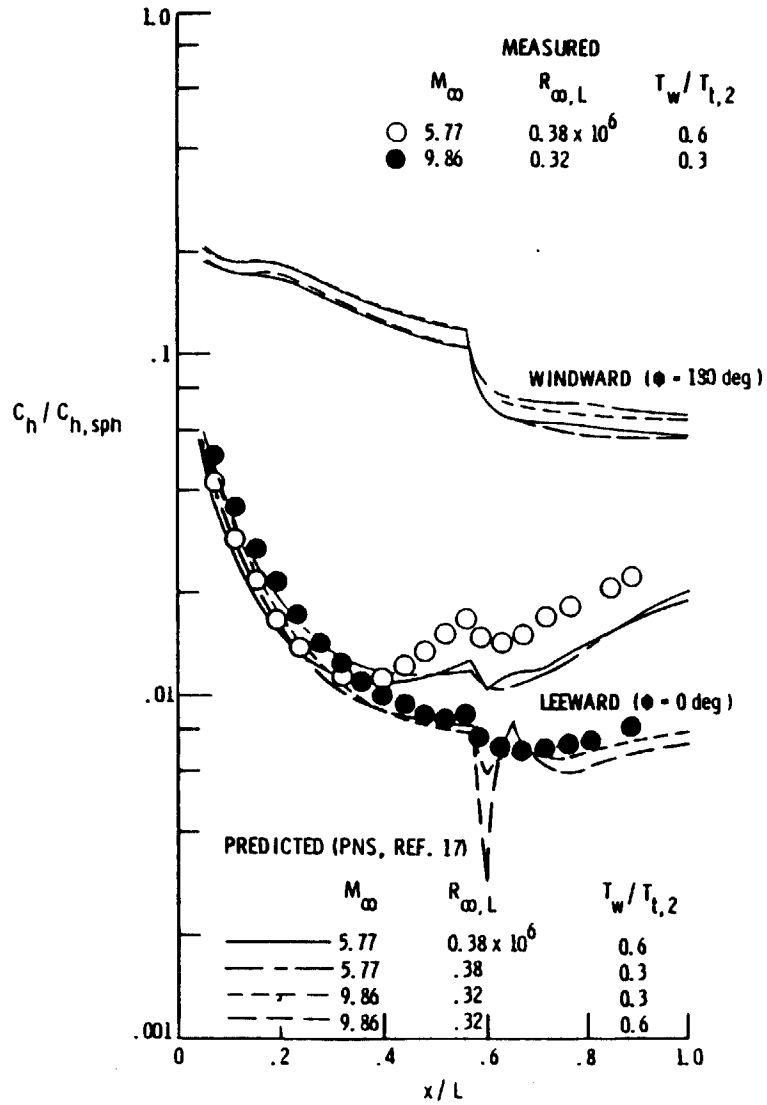
EFFECT OF REYNOLDS NUMBER ON CIRCUMFERENTIAL LEEWARD HEATING

$M_\infty \approx 10$ $\alpha = 12°$



EFFECT OF MACH NUMBER AND WALL TEMPERATURE RATIO

STRAIGHT BICONIC $\alpha = 12^{o}$



HALIS ORBITER

This study was initiated to verify the Langley developed HALIS (High ALpha Inviscid Solution) code. A geometry package that accurately duplicates the forward 93-percent length of the Shuttle Orbiter windward surface was developed and incorporated into HALIS: the leeward or upper surface was formed using elliptical cross-sections. This Euler code was first written for perfect gases, for which the basic inputs were Mach number and ratio of specific heats (gamma) or effective gamma, and later modified by including the thermodynamic relations for CF_4 and curve fits for real air in thermochemical equilibrium. Force and moment tests have been performed in the Mach 6, CF_4, and Mach 10 tunnels for angles of attack up to 45° and the test results compared to prediction. With the exception of the pitching moment at Mach 6 in air, the agreement is either quite good or it follows some expected departure such as underprediction of the axial force coefficient by the inviscid code. Oil flow patterns have been obtained at Mach 6 in air that illustrate the complexity of the flow over the leeward surface at these high angles of attack.

Two thin film heat transfer models have been fabricated, one of stainless steel and the other of MACOR, to verify predictions obtained from a 3-dimensional, axisymmetric analog (3DAA) boundary layer code coupled to the HALIS code, and a VSL (Viscous Shock Layer) code. Instrumented substrates will be interchangeable between the models. Two different materials are being used for structural reasons/concerns and to determine if mismatches in thermal conductivity between the substrate and model cause a measurable effect on the heating levels. These models will be instrumented with thin film gages only on the windward (bottom) surface; instrumentation was restricted to the bottom surface because the HALIS-3DAA codes and VSL code are not applicable to the separate flow region on the leeward side. However, recently recorded leeward surface streamline patterns of significant interest and the possible application of a Navier-Stokes code to this configuration have resulted in plans to instrument the leeward (upper) side. Pressure models containing orifices on the windward and the leeward surfaces are also being designed.

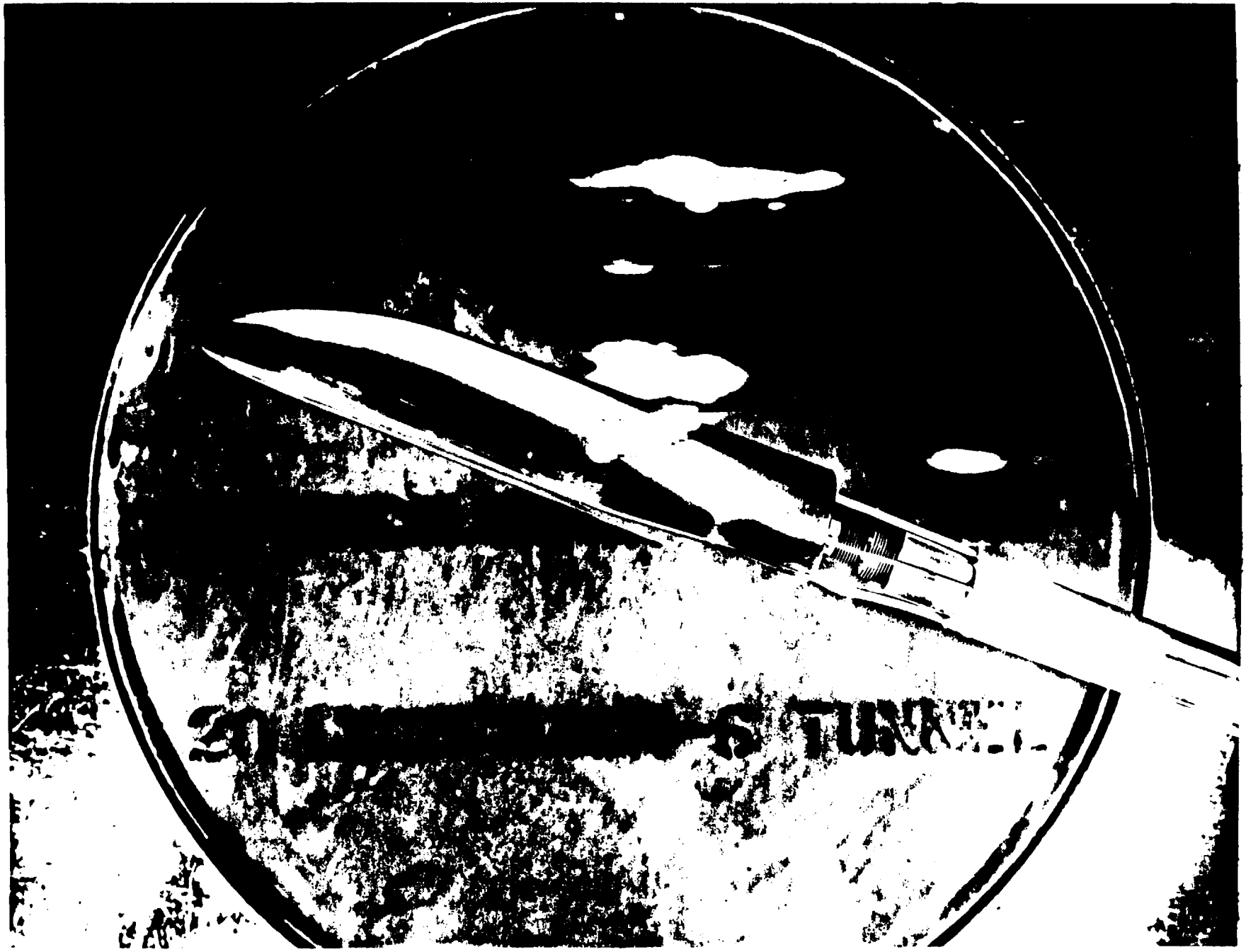
References:

1. Weilmuenster, K. James and Hamilton, H. Harris, II, "A Method for Computation of Inviscid Three-Dimensional Flow over Blunt Bodies Having Large Embedded Subsonic Regions," AIAA Paper No. 81-1203, June 23-25, 1981.

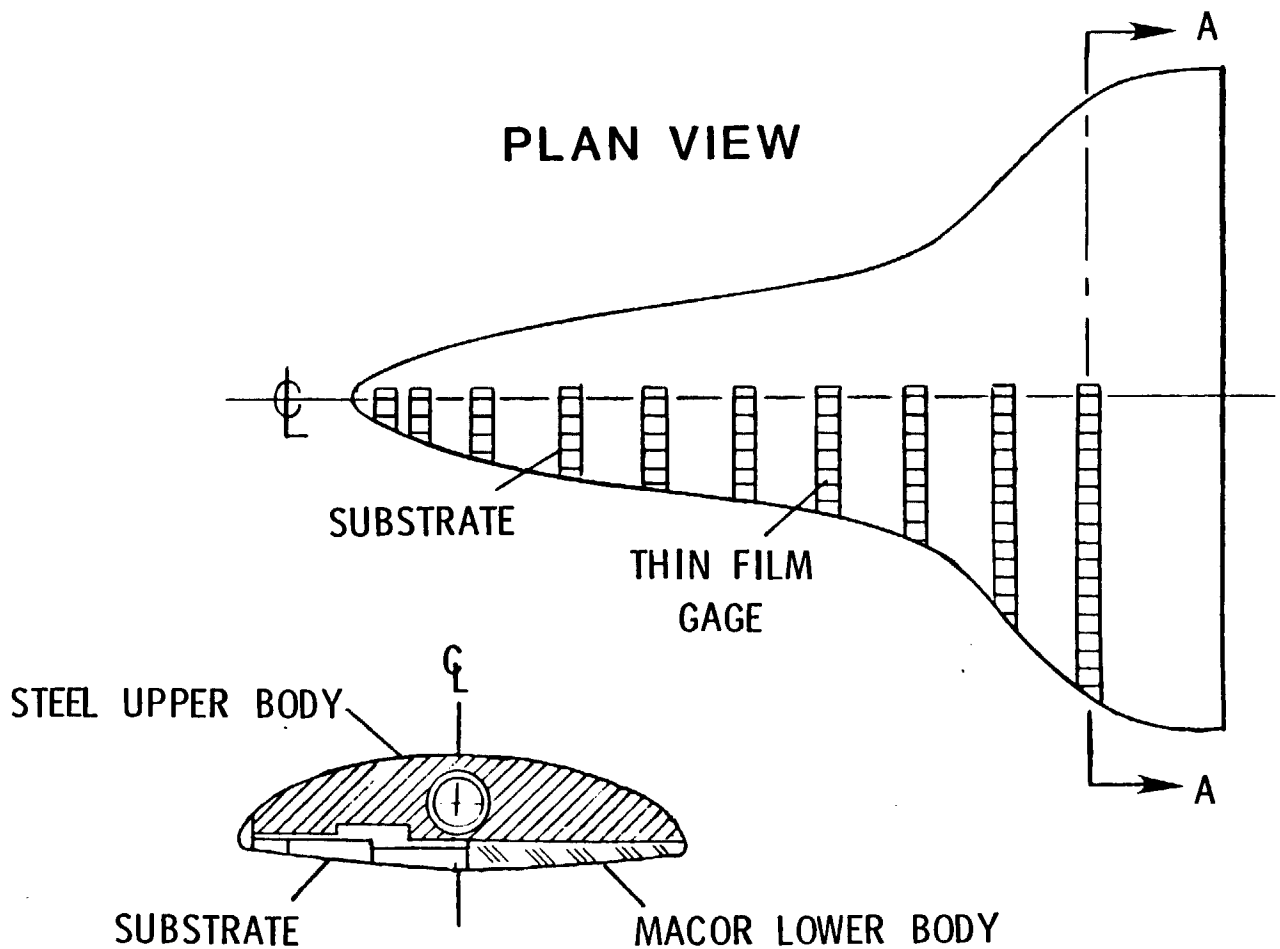
2. Weilmuenster, K. James and Hamilton, H. Harris, II, "A Comparison of Computed Space Shuttle Orbiter Surface Pressures with Flight Measurements," AIAA Paper No. 82-0937, June 7-11, 1982.

3. Micol, J. R. and Weilmuenster, K. J., "Experimental Aerodynamic Coefficients on a Shuttle-Like Vehicle at Mach 6 and 10 and Comparison to Prediction," AIAA Paper No. 85-1796, August 19-21, 1985.

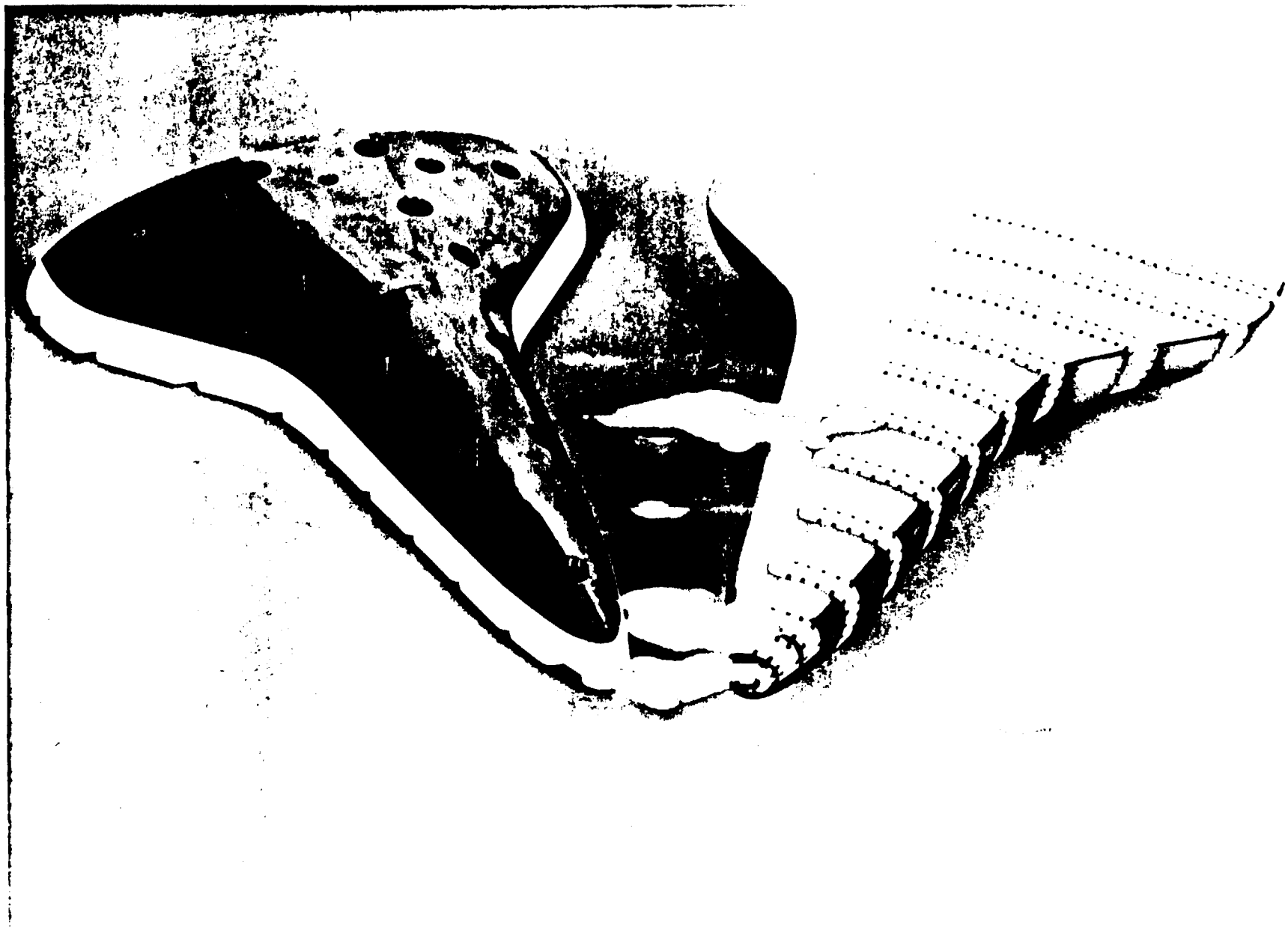
HALIS ORBITER CODE VERIFICATION MODEL



HALIS ORBITER SPANWISE HEATING STUDY



HALIS ORBITER SPANWISE HEATING MODEL



AEROASSIST ORBITAL TRANSFER VEHICLE (AOTV) WITH PAYLOAD

Detailed pressure and heating distributions will be measured over an axisymmetric drag brake, proposed by the Ames Research Center, for an angle of attack range of 0° to 20°. The drag brake is an analytical description of a spherically blunted, 70° half angle cone with a bluntness ratio of unity and with a small skirt. A cylinder whose length and diameter simulate a payload sized for the shuttle orbiter payload bay is attached to the base of the brake. The front surface of the brake is instrumented, as are the base and the cylindrical payload. Pressure and heat transfer (thin film) models have been fabricated with diameters of 2.5 in. and 4.0 in. so that tests can be performed in all tunnels of the Langley HFC. The primary purpose of this study is to verify a Navier-Stokes code developed at Langley which uses a finite-volume, adaptive-grid algorithm. Of particular interest is the ability of this code to accurately predict surface properties on the base and along the cylindrical payload.

A related CFD code calibration study involves the measurement of detailed heating distributions on a family of spherically blunted cones having cone half angles of 50°, 60° and 70°, base diameter equal to 4 inches, and sharp and rounded corners. Heat transfer measurements on the forebody of each model were obtained using the continuous thin skin, transient calorimeter technique; heating distributions on the base of models with rounded corners were measured using thin film gages. These models have been tested in the Langley 20-Inch Mach 6 Tunnel at values of free stream Reynolds number based on model diameter from 0.2 to 2.6 million and angles of attack from 0 to 20° in 5° increments. Attempts to test these sphere cone models in the CF_4 Tunnel were successful only for the 50° and 60° models. A disturbance on the nozzle centerline of this facility requires that models be tested in the uniform portion of the flow between the nozzle centerline region and the nozzle boundary layer at the test section; unfortunately, this uniform flow region was insufficient for the 70° models. Preliminary comparisons of predictions from the HALIS-3DAA codes to measurement have been performed.

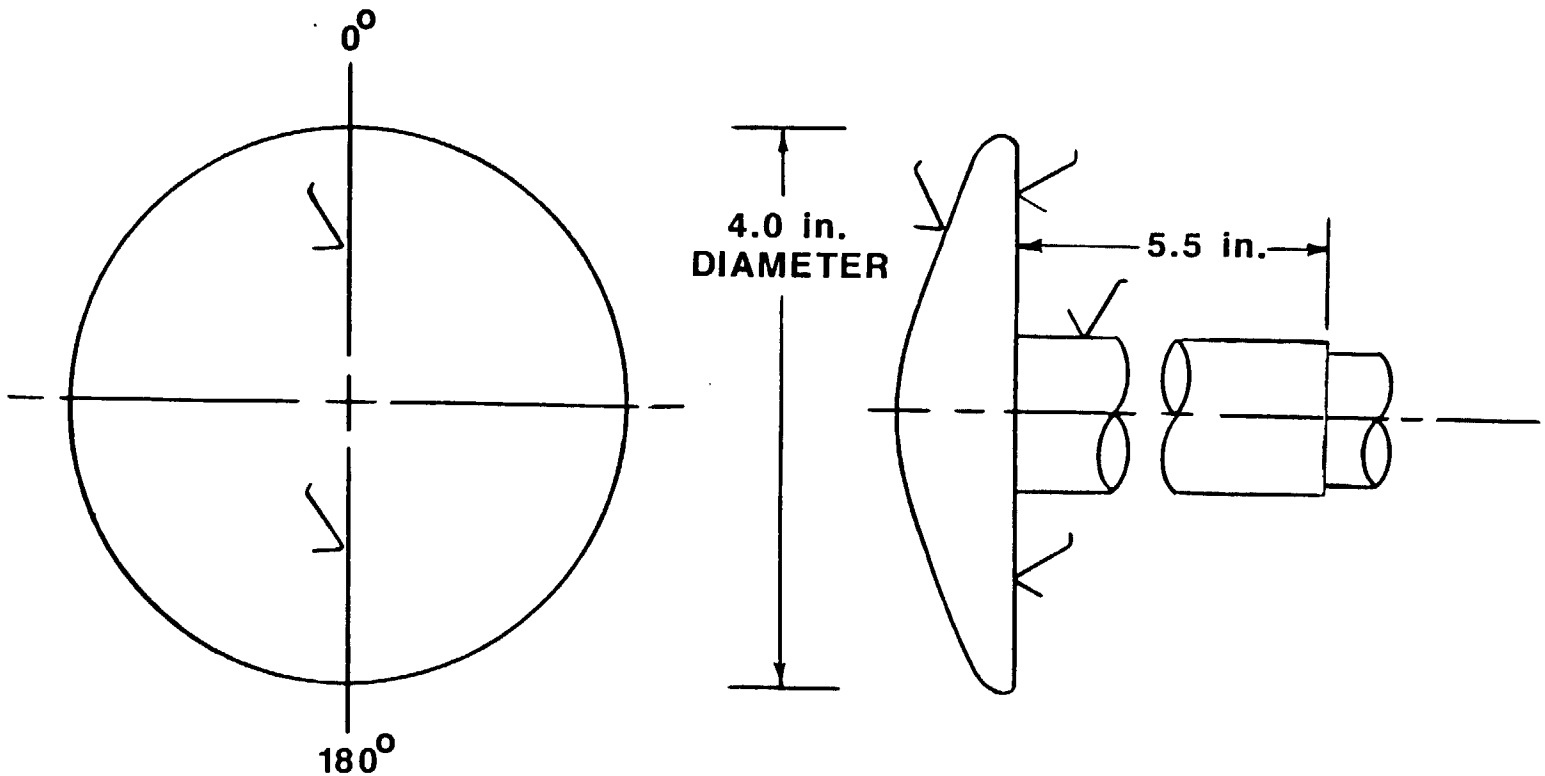
Reference:

1. Gnoffo, Peter A., "Complete Flowfields Over Low and Wide Angle AOTV Conceptual Configurations," AIAA Paper 84-1695, June 25-28, 1984.

AEROBRAKE CODE VALIDATION MODELS

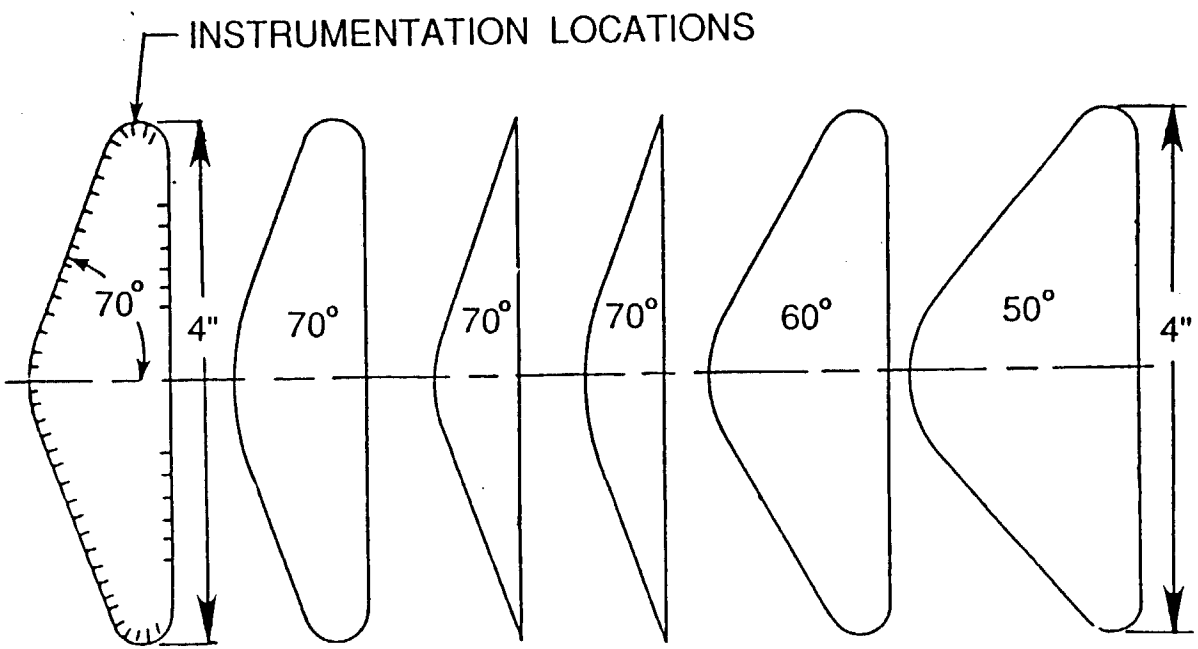
FORCE AND MOMENT

	PRESSURE	HEAT TRANSFER–THIN FILM
WINDWARD	31	29
BASE	6	14
PAYLOAD	29	23



LOCATION OF INSTRUMENTED RAYS INDICATED BY √

SPHERE CONE HEAT TRANSFER MODELS



FOREBODY - CONTINUOUS THIN SKIN; TRANSIENT CALORIMETER
BASE - THIN FILM RESISTANCE GAGES

C-4

HYPERSONIC NOZZLES

As a consequence of proposed CFD code calibration studies planned for the Langley Hypersonic Facilities Complex, measurements of detailed pitot pressure surveys have been made at the test section of most hypersonic wind tunnels in recent years. These surveys revealed the flow was relatively uniform for facilities having two-dimensional or three-dimensional contoured nozzles, but was not uniform for facilities having axisymmetric contoured nozzles. Thus, replacement nozzles are sought that will provide uniform flow for these facilities, which use air, nitrogen, helium, or CF_4 as the test gas. Because of the large expense associated with the fabrication of a nozzle contour to small tolerances, it is important that the credibility of the codes used to predict the nozzle aerolines be established, as well as the validity of the inputs. An effort is underway at Langley to compute nozzle aerolines for the Hypersonic CF_4 Tunnel, Hypersonic Nitrogen Tunnel, and Hypersonic Helium Tunnel. The nozzle design procedure being utilized is presented in NASA TM 89042 and the final coordinates will be obtained using a Navier Stokes code. The criteria established for flow uniformity in the axial and radial directions at the test section is pitot pressure (a measurable quantity) to within 0.1 percent. Credibility of the codes being utilized is established by comparing test section pitot pressure distributions predicted for an existing nozzle contour (measured coordinates) to those measured (see NASA TM 89042); that is, the nozzle codes are being "calibrated" prior to the application of these codes for the computation of new aerolines.

References:

1. Miller, C. G. and Smith, F. M., "Langley Hypersonic Facilities Complex - Description and Application," AIAA Paper No. 86-0741-CP, March 1986.

2. Miller, C. G., "A Status Report on the Langley Hypersonic Facilities Complex," Presented at the 67th Semi-Annual Meeting of the Supersonic Tunnel Association, April 1987.

3. Thompson, R. A. and Sutton, K., "Computational Analysis and Preliminary Redesign of the Nozzle Contour of the Langley Hypersonic CF_4 Tunnel," NASA TM 89042, March 1987.

4. Erlebacher, G., et al., "A Computational Design Procedure for Actively Cooled Hypersonic Wind-Tunnel Nozzles Subject to Wall Shape Constraints," Paper presented at CFD in Aerospace Design Workshop (Tullahoma, TN), University of Tennessee Space Institute, June 4-6, 1985.

AEROLINES FOR HYPERSONIC WIND TUNNEL NOZZLES

- REPLACEMENT AXISYMMETRIC CONTOURED NOZZLES REQUIRED FOR:

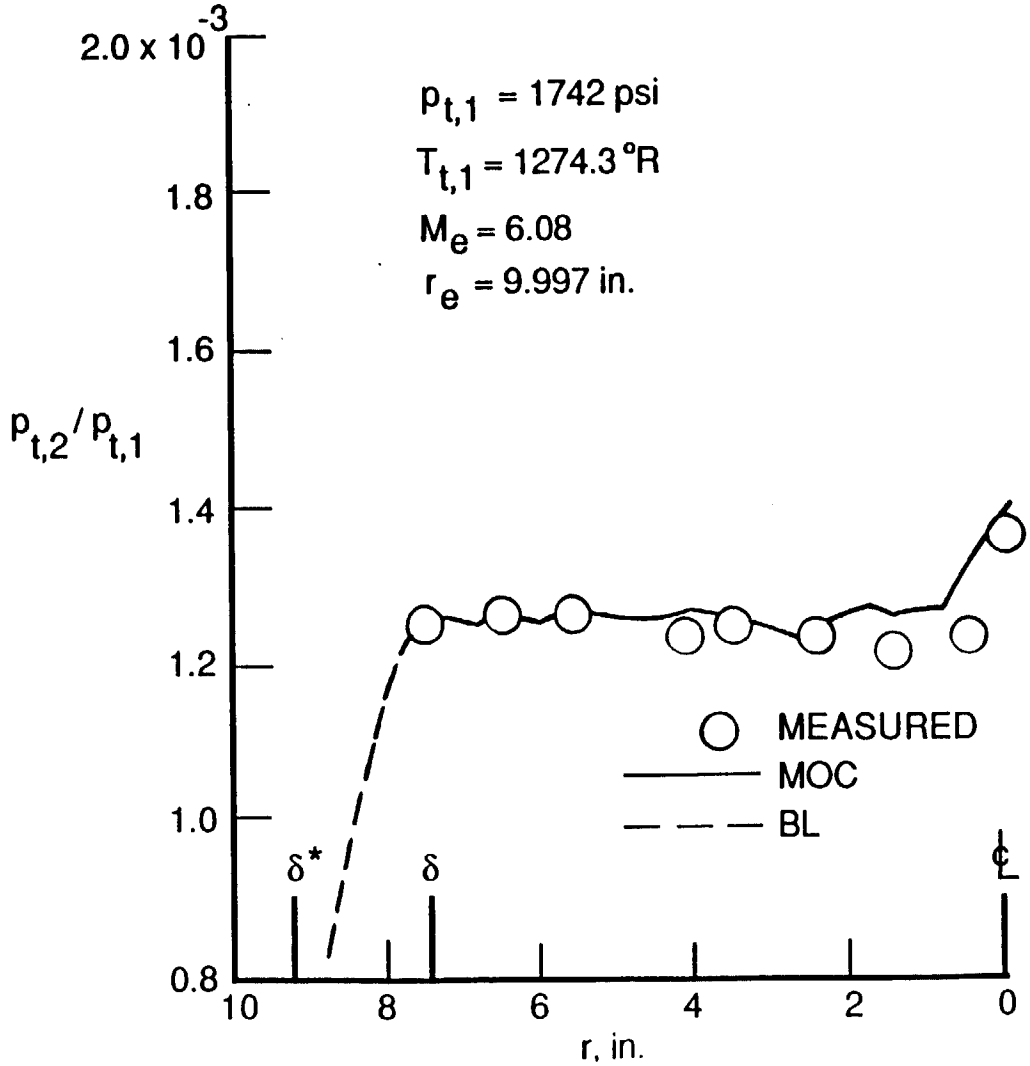
FACILITY	TEST GAS	P_O ,PSI	T_O ,°R	MACH NO.	EXIT DIAM. IN.
CF_4 TUNNEL*	CF_4	1600	1260	5.9	20
NITROGEN TUNNEL*	N_2	4500	3400	17.0	20
HELIUM TUNNEL	He	2000	540	20.0	22
M = 8 VDT *	AIR			To be determined	

* PRESENTLY UNDER DESIGN

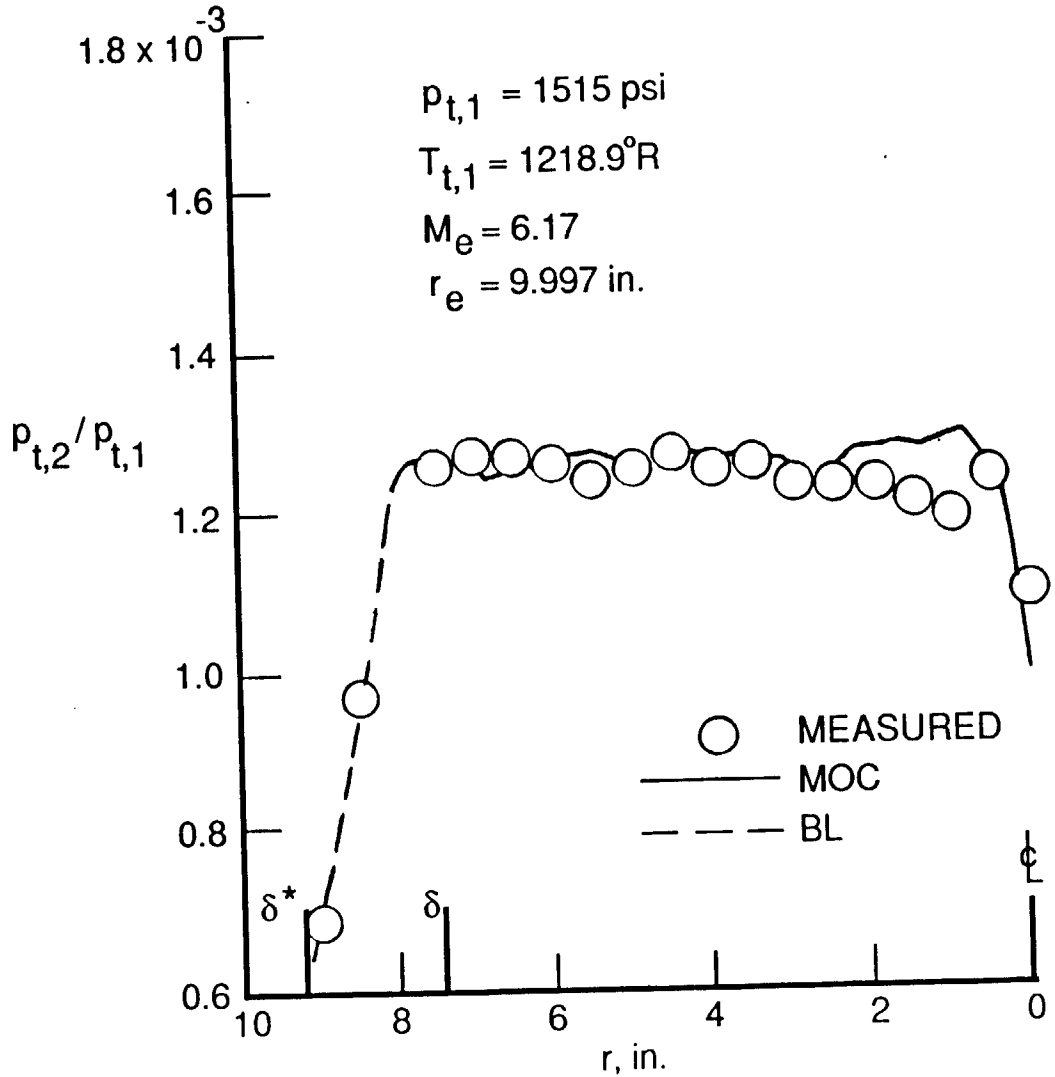
- CONSIDERATIONS
  - INTERMOLECULAR FORCE EFFECTS
  - VIBRATIONAL EXCITATION (EQ, NONEQ, FROZEN)
  - THERMODYNAMIC / TRANSPORT PROPERTIES AT LOW TEMPERATURES
  - LIQUEFACTION
  - UNCERTAINTY IN WALL TEMPERATURE DISTRIBUTION
  - LARGE DISCONTINUITIES IN WALL TEMPERATURE DISTRIBUTION
  - TRADES ON EXPANSION RATE JUST DOWNSTREAM OF THROAT
  - TRADES ON MAXIMUM TURNING ANGLE
  - FINITE DISPLACEMENT THICKNESS IN THROAT REGION (HEATED OR COOLED)
  - AEROLINES PREDICTED FOR HOT WALL, BUT MACHINE AT AMBIENT TEMPERATURE
  - SURFACE WAVINESS
  - SURFACE FINISH
  - OFF - DESIGN PERFORMANCE

- CREDITABILITY OF PREDICTION TECHNIQUE ESTABLISHED BY ABILITY OF CODE TO PREDICT PITOT PRESSURE DISTRIBUTIONS MEASURED WITH EXISTING NOZZLES

MEASURED AND PREDICTED PITOT PRESSURE PROFILES AT NOZZLE EXIT OF LANGLEY HYPERSONIC CF_4 TUNNEL



MEASURED AND PREDICTED PITOT PRESSURE PROFILES AT NOZZLE EXIT OF LANGLEY HYPERSONIC CF_4 TUNNEL



AEROASSIST FLIGHT EXPERIMENT (AFE)

A code verification study for a proposed AFE vehicle was formulated during a parametric wind tunnel study of a Johnson Space Center concept proposed for the AFE. The basic configuration is an elliptically-blunted 60° half-angle cone whose base plane has been raked 17° to the vertical and a skirt attached to the base. High fidelity force and moment, pressure, and heat transfer (thin skin and thin film) models were fabricated for testing in the Mach 6, CF_4, and Mach 10 tunnels (model diameter equal to 3.7 in.) and the nitrogen and helium tunnels (model diameter equal to 2.5 in.). The surface contours of these AFE models were provided by the CFD code and machined to very close tolerances. The larger diameter pressure model has 64 orifices on just half the front surface thereby providing detailed pressure distributions. Force and moment measurements and pressure distributions have been compared to HALIS and to a Navier-Stokes code developed at Langley by P. A. Gnoffo and referred to as LAURA (Langley Aerothermodynamic Upwind Relaxation Algorithm); preliminary heating distributions have been compared to the HALIS-3DAA codes.

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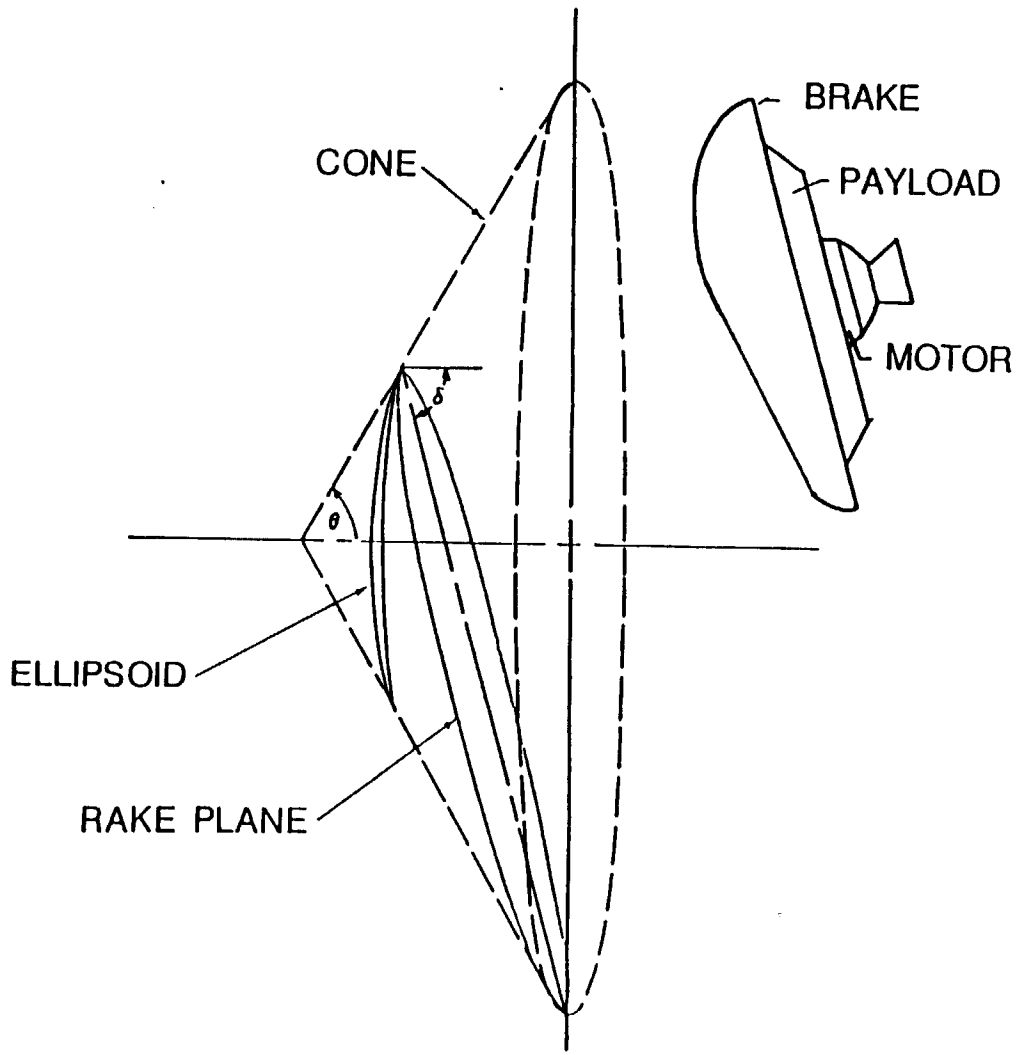
AEROASSIST FLIGHT EXPERIMENT

1986 - 1987 CATAGORY C - EXPERIMENTS DESIGNED TO CALIBRATE CFD CODES

1993 - 1994 CATEGORY D - EXPERIMENTS DESIGNED TO VALIDATE CFD CODES

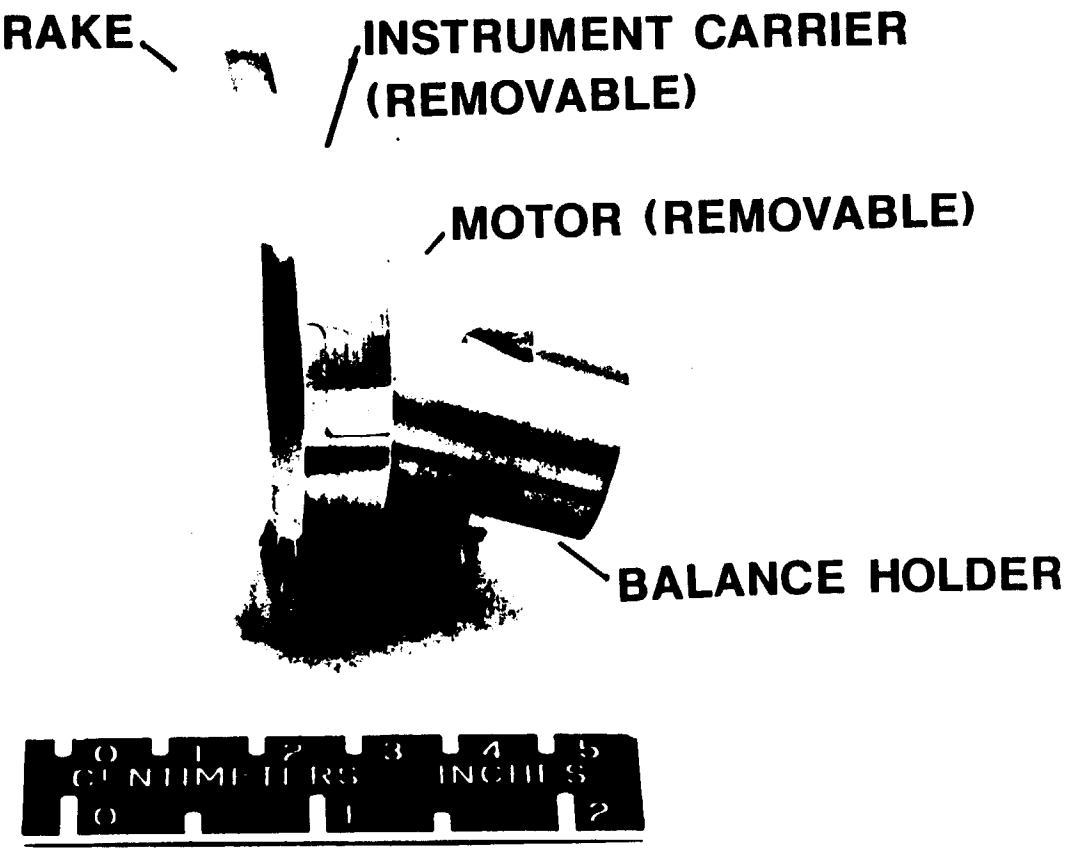
Reference: "THE RATIONALE FOR AN AEROASSIST FLIGHT EXPERIMENT" BY JIM J. JONES, AIAA PAPER NO. 87 - 1508

DEVELOPMENT OF AFE VEHICLE CONFIGURATION FROM ORIGINAL ELLIPTIC CONE

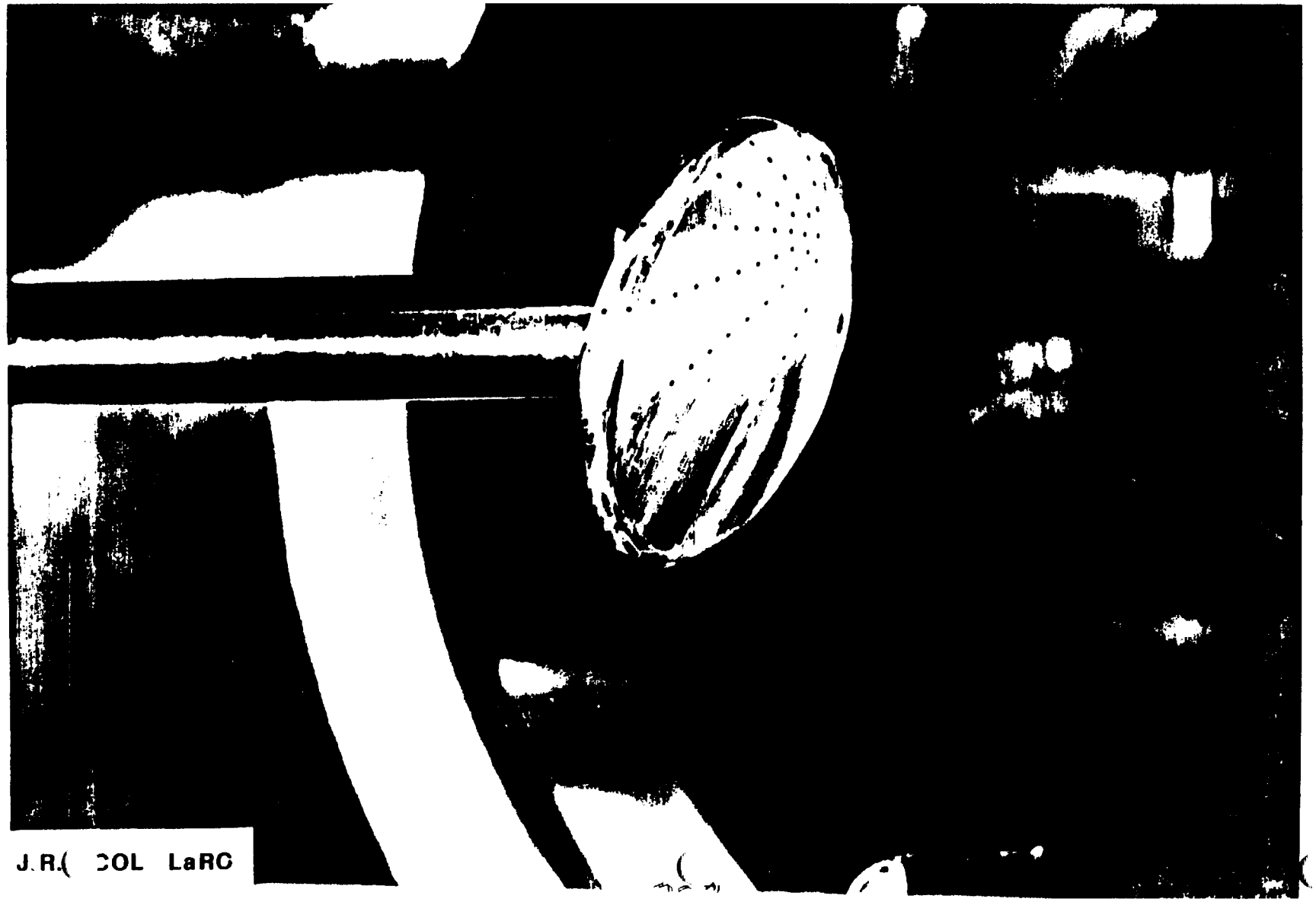


NASA
L-86-10,503

AFE FORCE AND MOMENT MODEL



AFE PRESSURE MODEL



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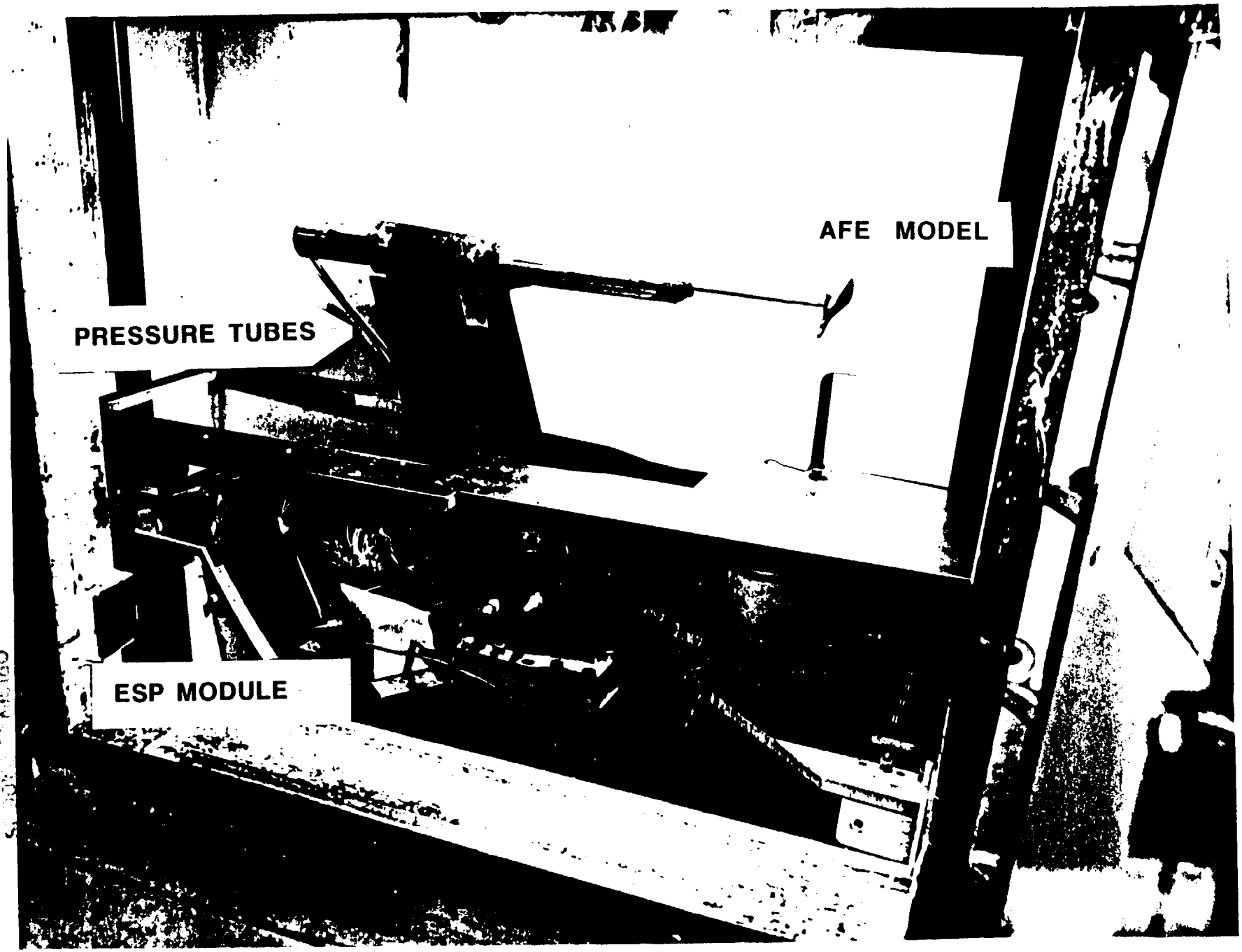
AFE PRESSURE MODEL IN 20-INCH MACH 6 TUNNEL



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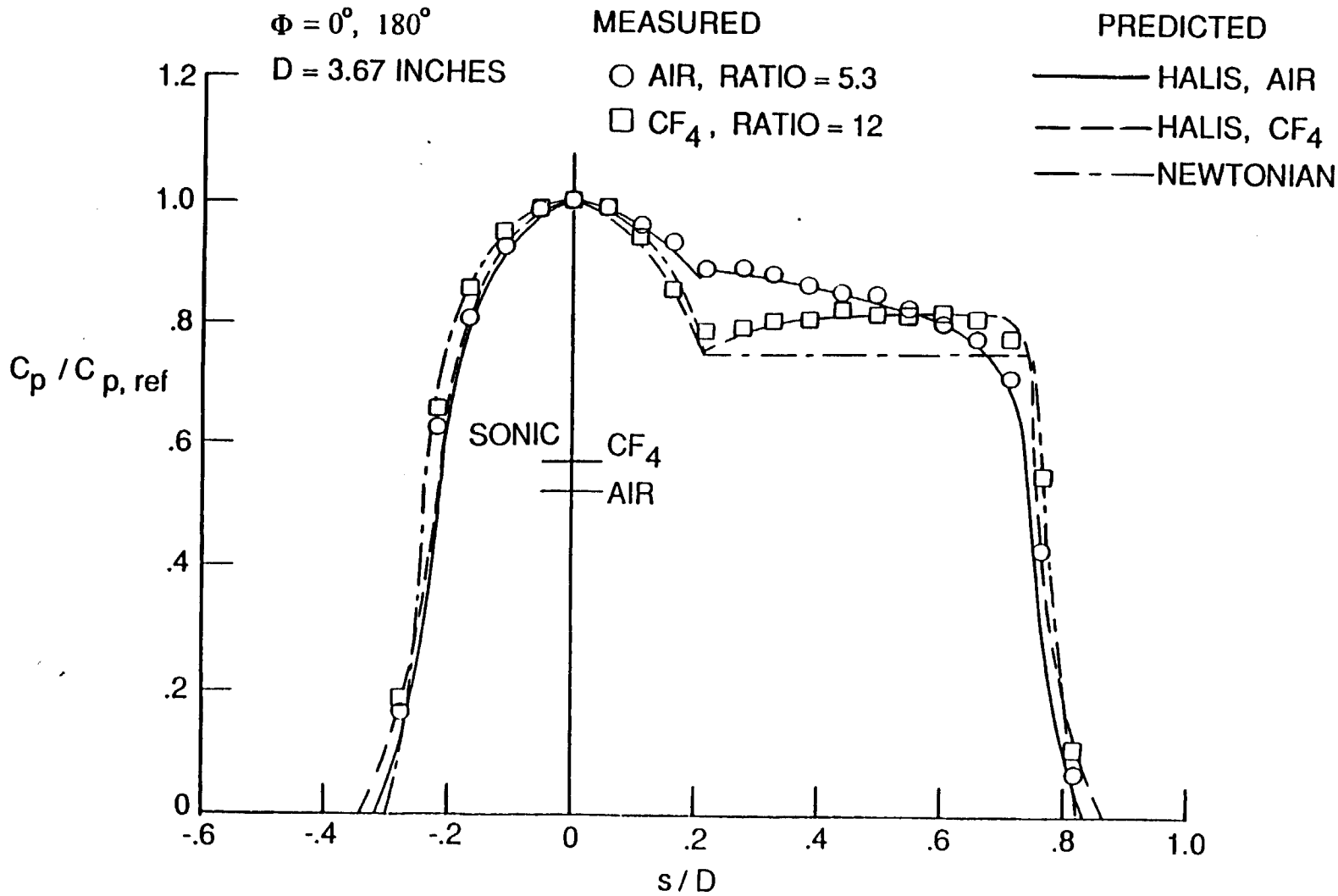
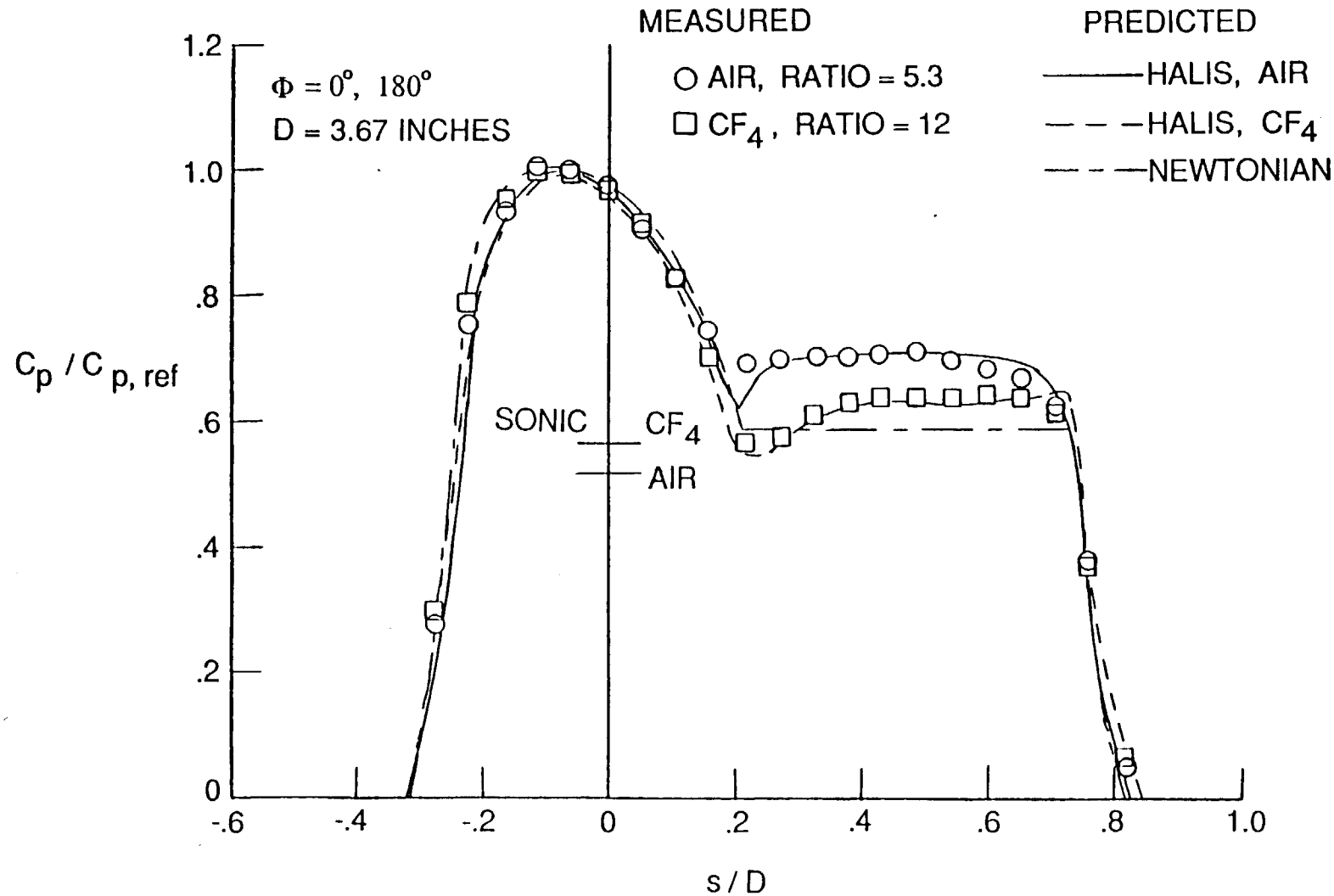
EFFECT OF DENSITY RATIO ON AFE PRESSURE DISTRIBUTION

MACH = 6 **α = 0 deg**

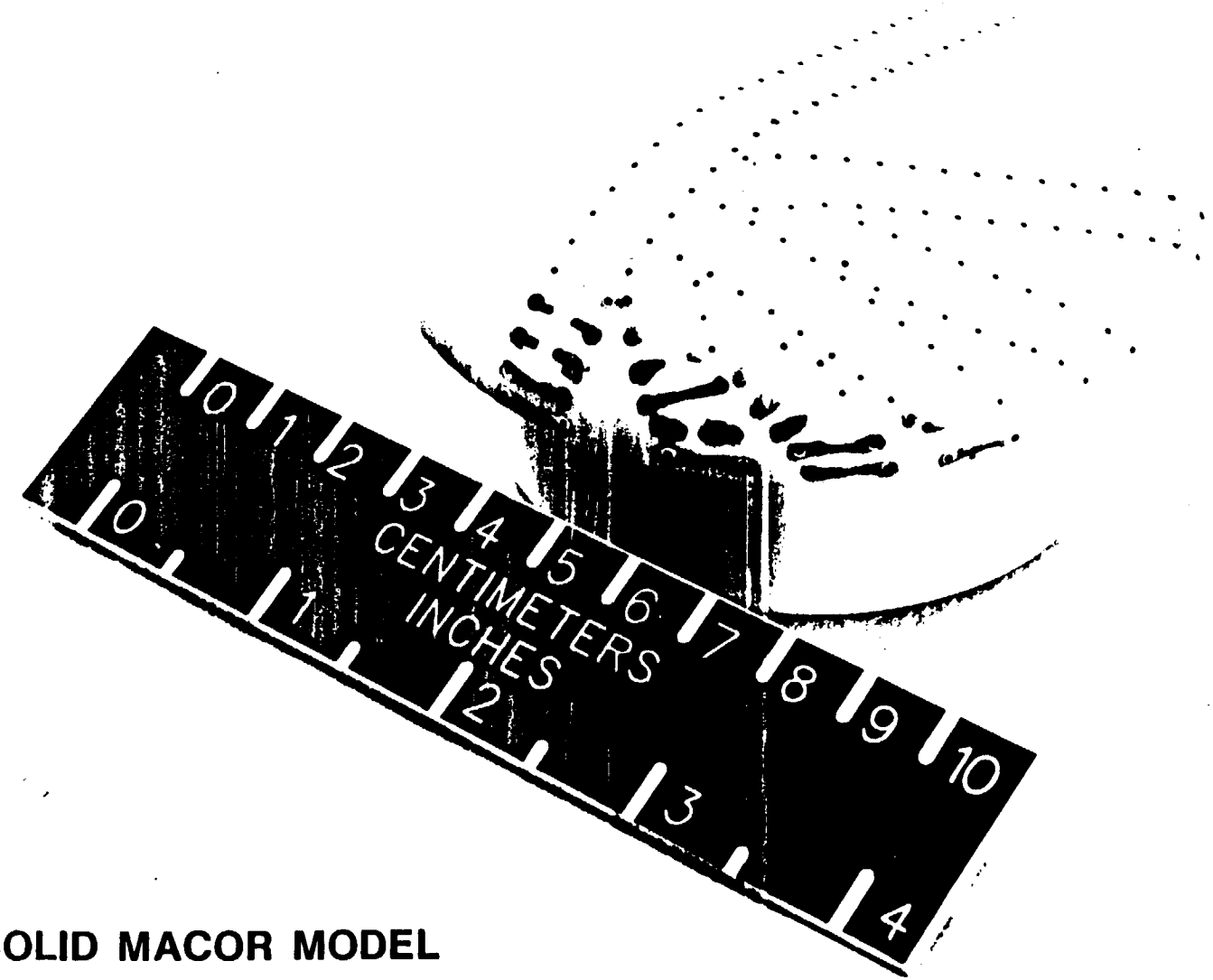


EFFECT OF DENSITY RATIO ON AFE PRESSURE DISTRIBUTION

MACH = 6 **α = -10 deg**



AFE THIN FILM HEAT TRANSFER MODEL

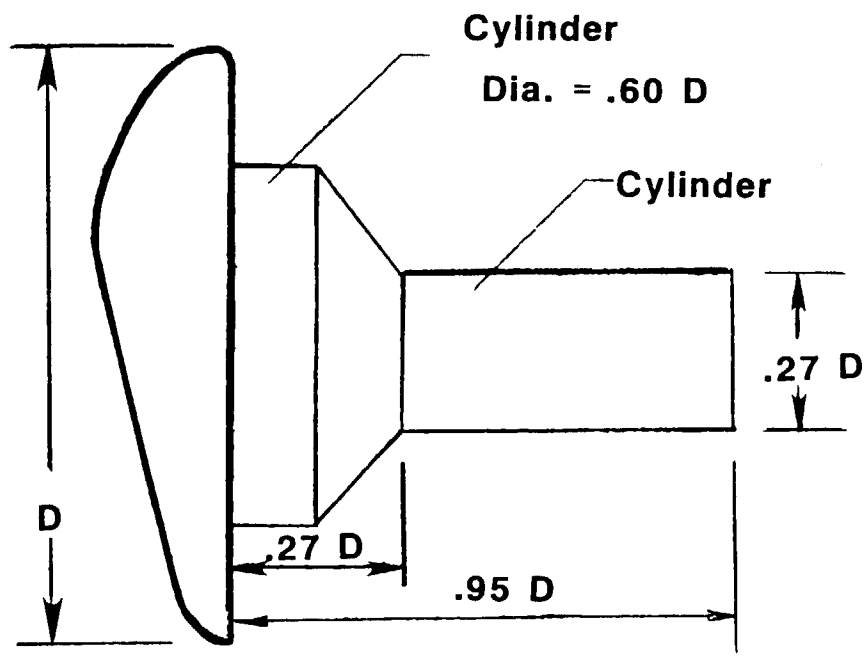


SOLID MACOR MODEL

PALLADIUM THIN FILM RESISTANCE GAGES

AFE "WAKE HEATING" MODEL

AFT CYLINDER INSTRUMENTED WITH THIN FILM RESISTANCE GAGES



COMPUTER CODE VERIFICATION STUDIES IN SUPPORT OF NASP

EXPERIMENT – LANGLEY HYPERSONIC FACILITIES COMPLEX

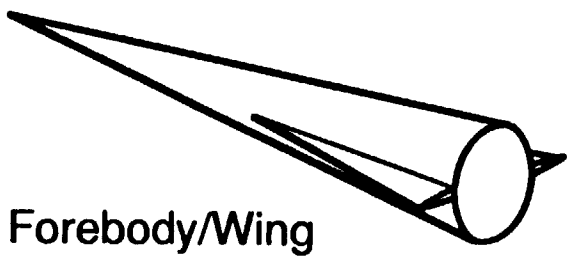
MEASUREMENTS

① Forces and moments
② Thermal mappings
③ Pressure distributions
④ Heat transfer distributions
⑤ Flow field surveys
⑥ Flow visualization

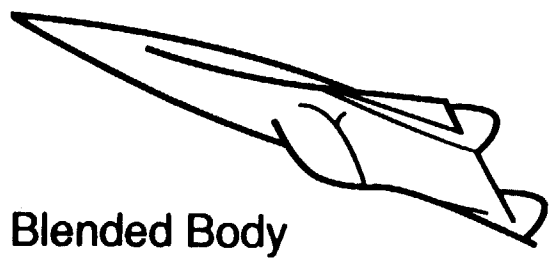
FLOW CONDITIONS

$6 < M < 22$
$0.2 \times 10^6 < R < 12 \times 10^6/ft$
$1.2 < \gamma < 1.7$
$0.3 < T_w/T_t < 1$

③④⑤⑥



Forebody/Wing



Blended Body

①②⑥

CFD CODES

- Navier Stokes
- Parabolized Navier Stokes
- Viscous Shock Layer
- Euler/Boundary Layer

ANALYTICAL CODE

- Aerodynamic Preliminary
- Analysis System (APAS)

EAB CODE VALIDATION STUDY FOR NASP

OBJECTIVE: Provide accurate, detailed surface and flowfield measurements on representative (but generic) forebody/wing configurations over a wide range of flow conditions in a timely manner.

APPROACH: Test forebody/wing configurations in LaRC Hypersonic Facilities Complex using established test techniques.

TEST CONFIGS:
Cone/wing (in progress)
Ogive (in progress)
Lifting body (being studied)

FLOW VARIABLES:

Mach No.	Gamma
6,10,17	1.4
6	1.2
20	1.67

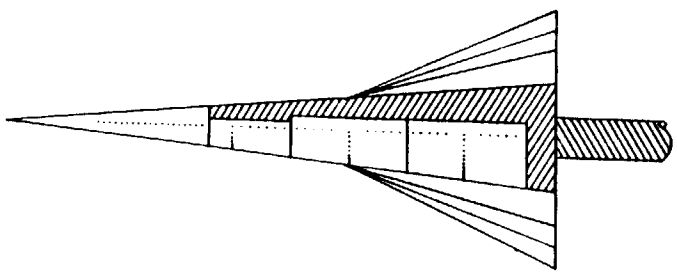
RN = .2 to 12 x 10^6 / ft
Tw / Tt = .15 to 1

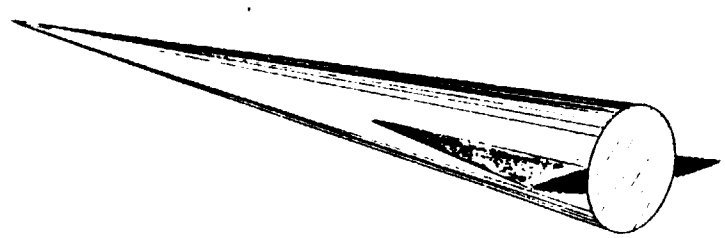
GEO. VARIABLES:
AOA = 0 to 20
Interchangable nose tips
Removable wings
Sting / base diameter ratio

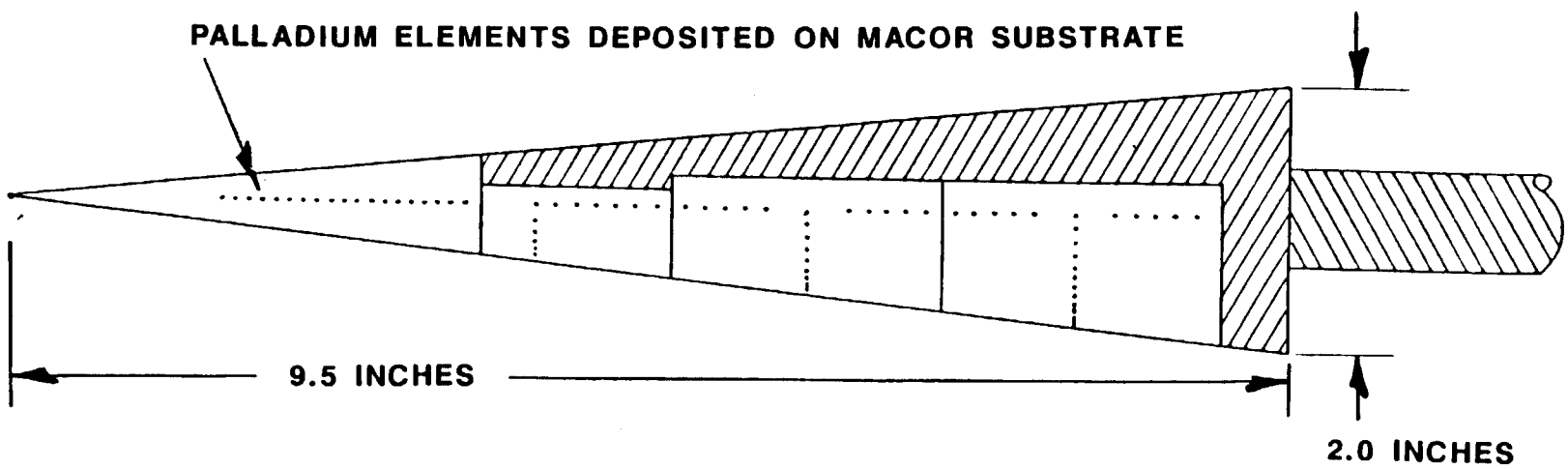
SKETCH OF CONE HEAT TRANSFER MODEL

$\Theta_c = 6°$

WINGED CONFIGURATION







TEST MATRIX FOR CFD CODE VALIDATION STUDY

MEASUREMENT	FACILITIES				
	20 - INCH MACH 6	31 - INCH MACH 10	CF_4	NITROGEN	HELIUM
Force and moment	●	●	●	●	●
Pressure	●	●	●	●	●
Heat transfer	●	●	●	●	
Thermal mapping	●	●	●	●	
Surface oil flow	●	●	●	●	●
Schlieren Electron beam	●		●	●	●
Flow field survey: Pitot pressure Total temperature Flow direction	●				●

OUTLINE OF CFD CODE CALIBRATION STUDIES

CONFIGURATION	MEASUREMENTS	FACILITIES	COMPUTER CODES
AFE	F&M, P, HT, FLOW VIS	M6T, M10T, CF4T, HHET	HALIS, 3DAABL, LAURA, APASII
AOTV W/PAYLOAD	P, HT, FLOW VIS	M6T, M10T, CF4T	SOFIA, LAURA*
SPHERE-CONES	HT, FLOW VIS	M6T, M10T, CF4T	HALIS, 3DAABL, LAURA*
HALIS ORBITER	F&M, HT, P, FLOW VIS	M6T, M10T, CF4T	HALIS, 3DAABL, VSL*
ELLIPTIC CONE	P, HT, FLOW VIS, FLOW ANGLE, SURFACE/FIELD	M6T, HHET	PNS*, NS*, VSL, STEIN*, LAURA*
BICONICS	HT, FLOW VIS	M6T, M10T, CF4T	PNS
FOREBODIES	P, HT, FLOW VIS, FLOW ANGLE, SURFACE/FIELD	M6T, M10T, CF4T, HHET	PNS*, NS*

*PLANNED OR CANDIDATE CODES

RECOMMENDATIONS FROM EXPERIMENTAL PERSPECTIVE

- HYPERSONIC WIND TUNNELS SHOULD BE CERTIFIED FOR CFD CODE CALIBRATION STUDIES

  STANDARDS (MEASURABLE) ADOPTED FOR:

  FLOW QUALITY
  - UNIFORMITY
  - TURBULENCE LEVEL
  - CONTAMINATION LEVEL
  - ACCURACY OF FLOW CONDITIONS

- NOZZLE CODES (MOC / EULER WITH BOUNDARY LAYER CODE; FULL NAVIER STOKES) SHOULD BE CALIBRATED WITH EXISTING HYPERSONIC WIND TUNNEL NOZZLE DATA

  CALIBRATED CODES USED TO COMPUTE AEROLINES FOR NOZZLES THAT PROVIDE UNIFORM FLOW

- DEVELOP STRONG ADVOCACY TO:
  - UPGRADE FACILITIES IN TERMS OF FLOW QUALITY
  - REFINE MEASUREMENT TECHNIQUES
    - INTRUSIVE FLOW FIELD
    - HEAT TRANSFER
    - PRESSURE
  - DEVELOP NON - INTRUSIVE FLOW FIELD DIAGNOSTIC TECHNIQUES

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DAVID A. THROCKMORTON 2-1-84

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HIGH ENTHALPY DETAILED AEROTHERMAL LOADS

BY

ALLAN R. WIETING

NASA LANGLEY RESEARCH CENTER
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AEROTHERMAL LOADS BRANCH

PRESENTED AT THE

FIRST NASA WORKSHOP ON CFD VALIDATION

NASA AMES RESEARCH CENTER
JULY 14-16, 1987

N92-70933

PRESENTATION OUTLINE

- MOTIVATION
- APPROACH
- PLANNED EXPERIMENTAL ACTIVITIES
- SHOCK-ON-LIP STUDIES
- MASS ADDITION COOLING STUDIES

MOTIVATION

- HIGH TEMPERATURE EFFECTS NOT NEGLIGIBLE
- FLUID-THERMAL-STRUCTURAL COUPLING IMPORTANT
- INTENSE LOCAL LOADS LEAD TO EARLY STRUCTURAL FAILURES
- REDUCED DESIGN MARGINS TO SAVE MASS

APPROACH

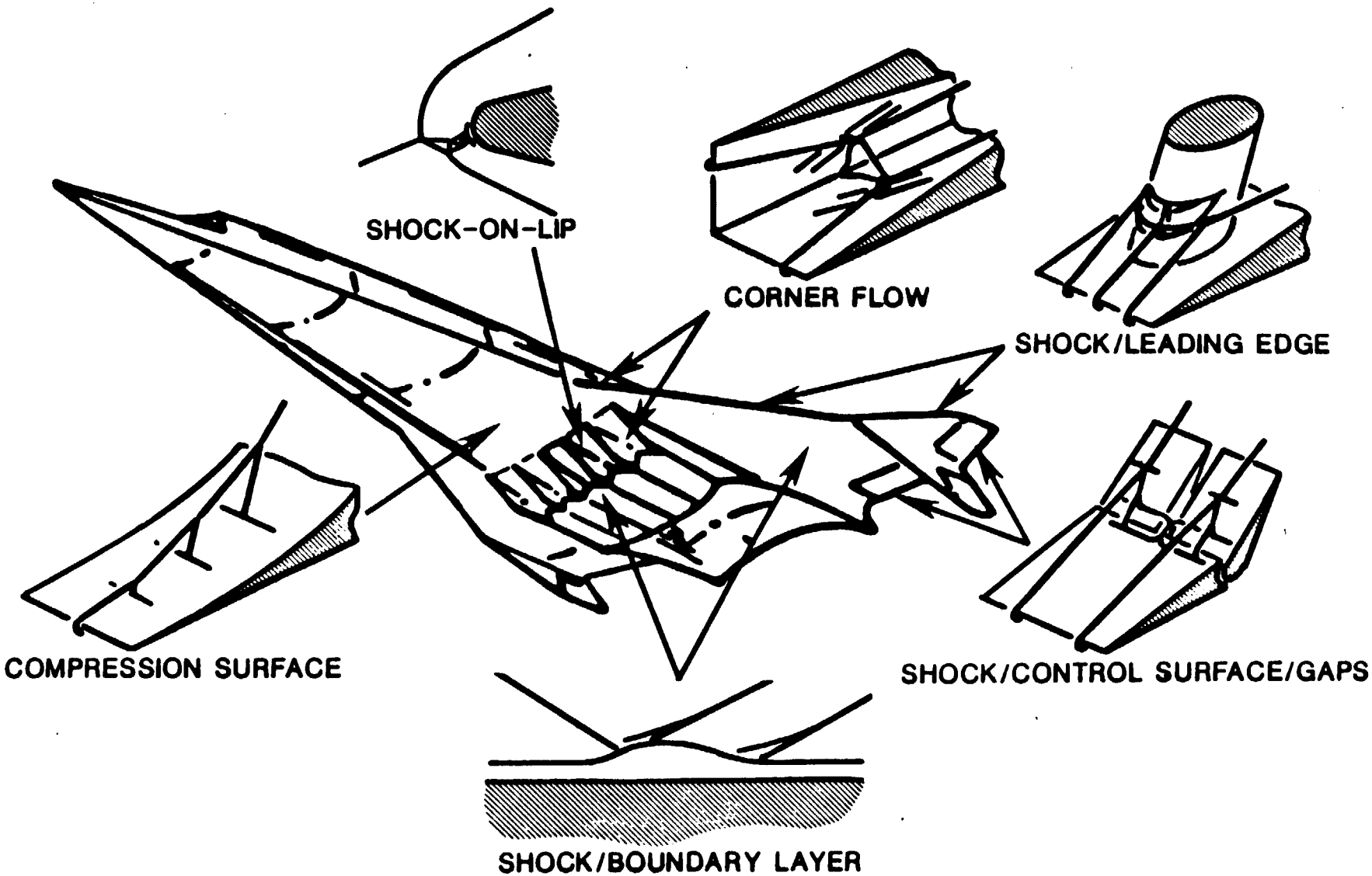
- NEW EXPERIMENTS FILL VOIDS IN DATA BASE
- PRIMARILY SURFACE MEASUREMENTS
  - PRESSURE
  - HEAT FLUX
  - SKIN FRICTION
- SCHLIEREN/HOLOGRAPHY
- RAKES

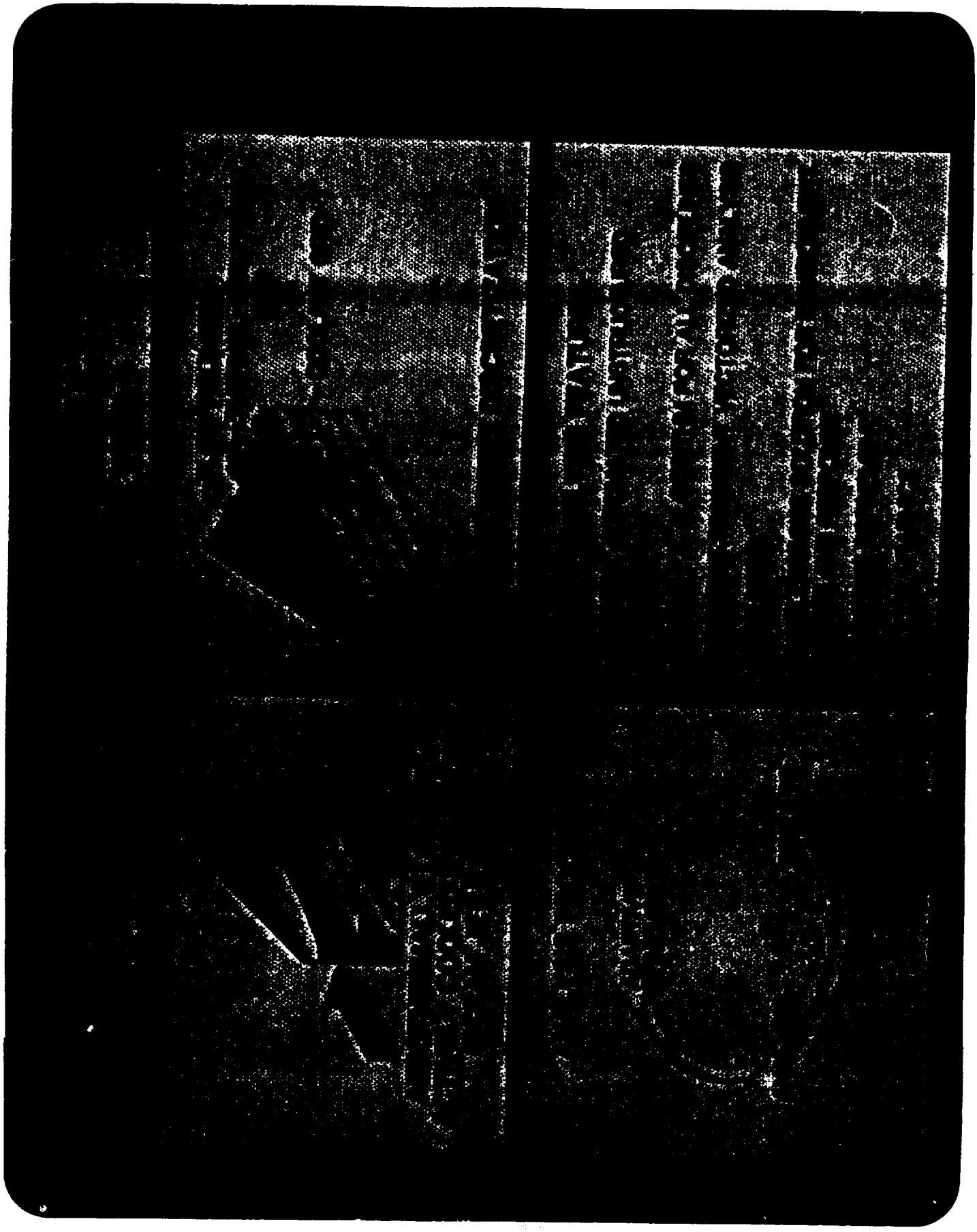
LIMITATION

- SURVIVABILITY OF INSTRUMENTATION IN HIGH ENTHALPY FLOW

AEROTHERMAL LOADS EXPERIMENTAL PROGRAM

DESIGN AND CODE VALIDATION DATA BASE





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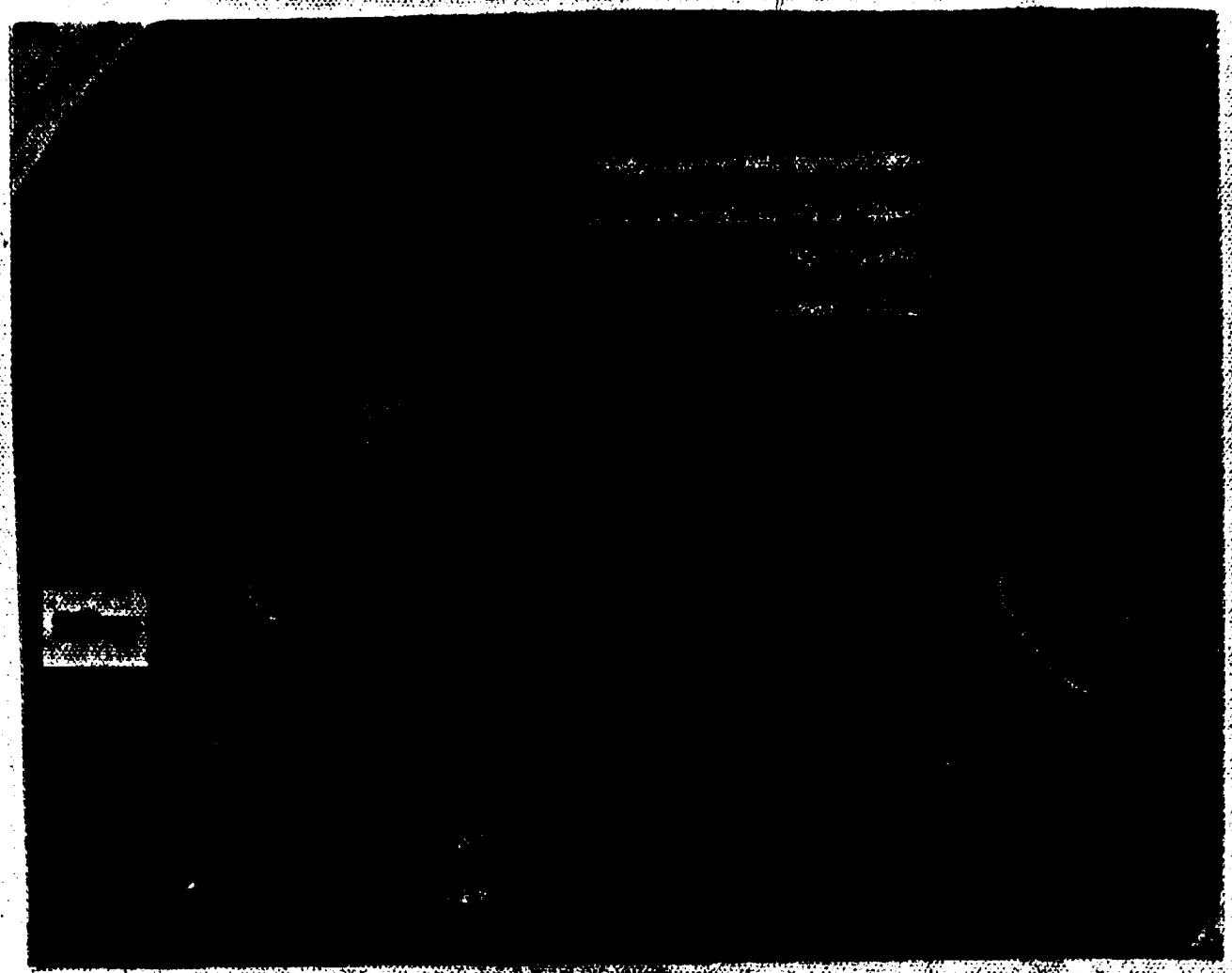
SHOCK INTERFERENCE MODEL MOUNTED IN
CALSPAN 48-inch HYPERSONIC SHOCK TUNNEL



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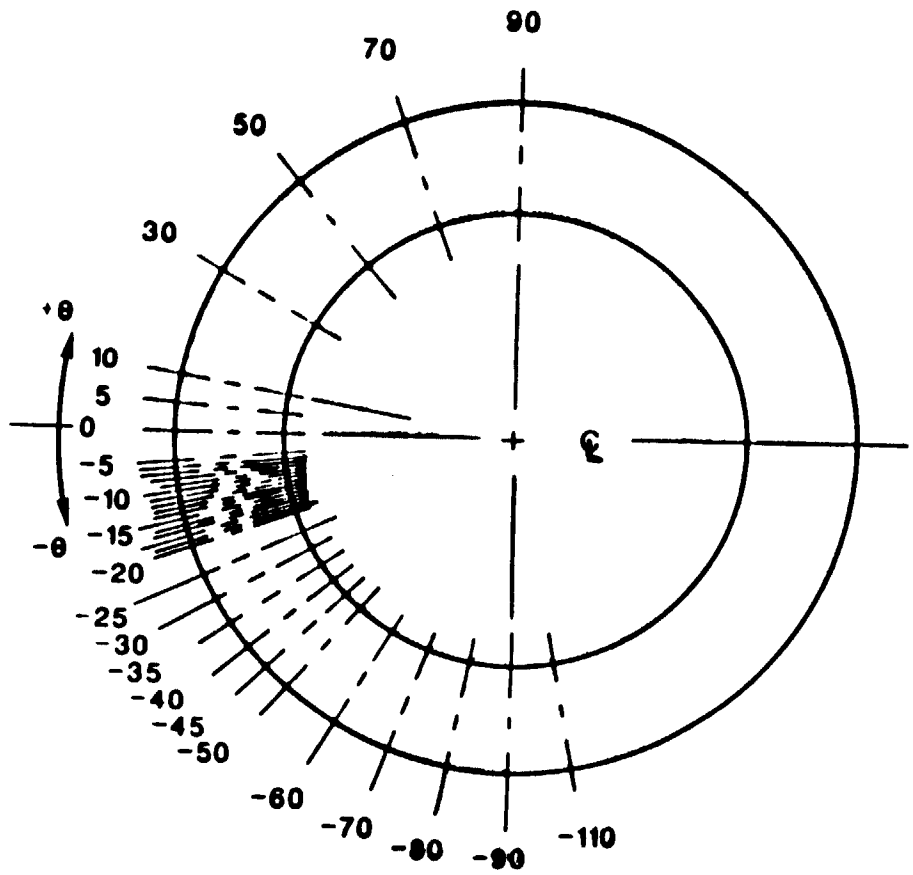
CYLINDER CIRCUMFERENTIAL INSTRUMENTATION LOCATION

LaRC 8-foot High Temperature Tunnel



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UNDISTURBED AND THIN W FLOW FIELDS

MACH 5.8

UNDISTURBED

[redacted]

[redacted] W INTERFERENCE

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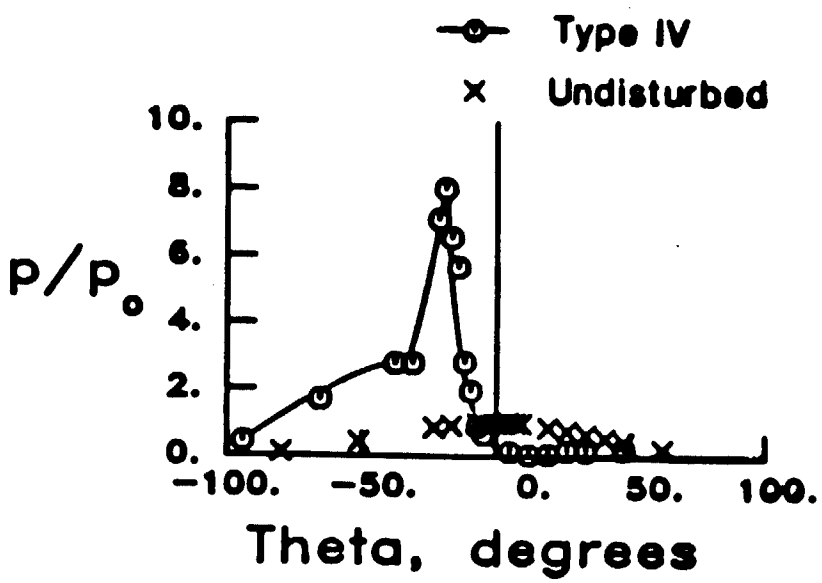
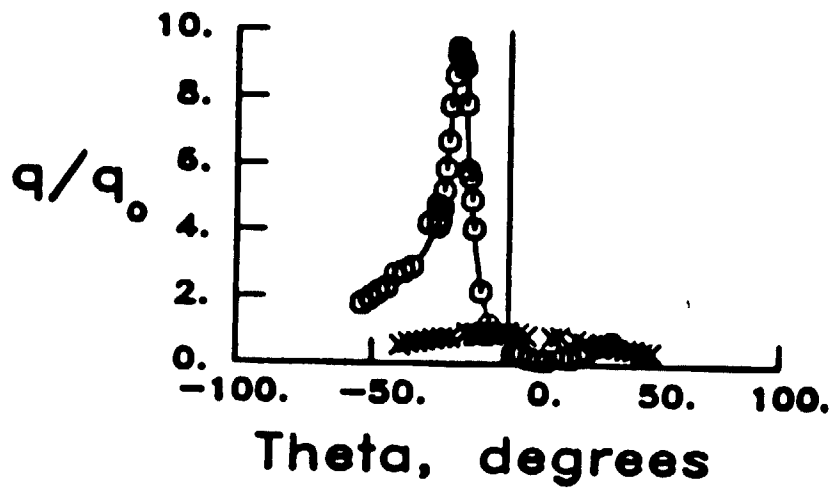
PRESSURE AND HEAT TRANSFER RATE DISTRIBUTIONS FOR A TYPE IV INTERFERENCE

$M = 8.0 \quad Re = 1.55 \times 10^6$ 1/ft $\quad \delta = 10$ degrees

PRESSURE DISTRIBUTION



HEAT TRANSFER RATE DISTRIBUTION

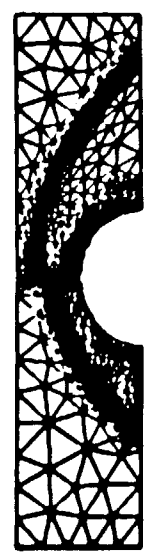


FINITE ELEMENT GRID EVOLUTION FOR INVISCID SOLUTION

First

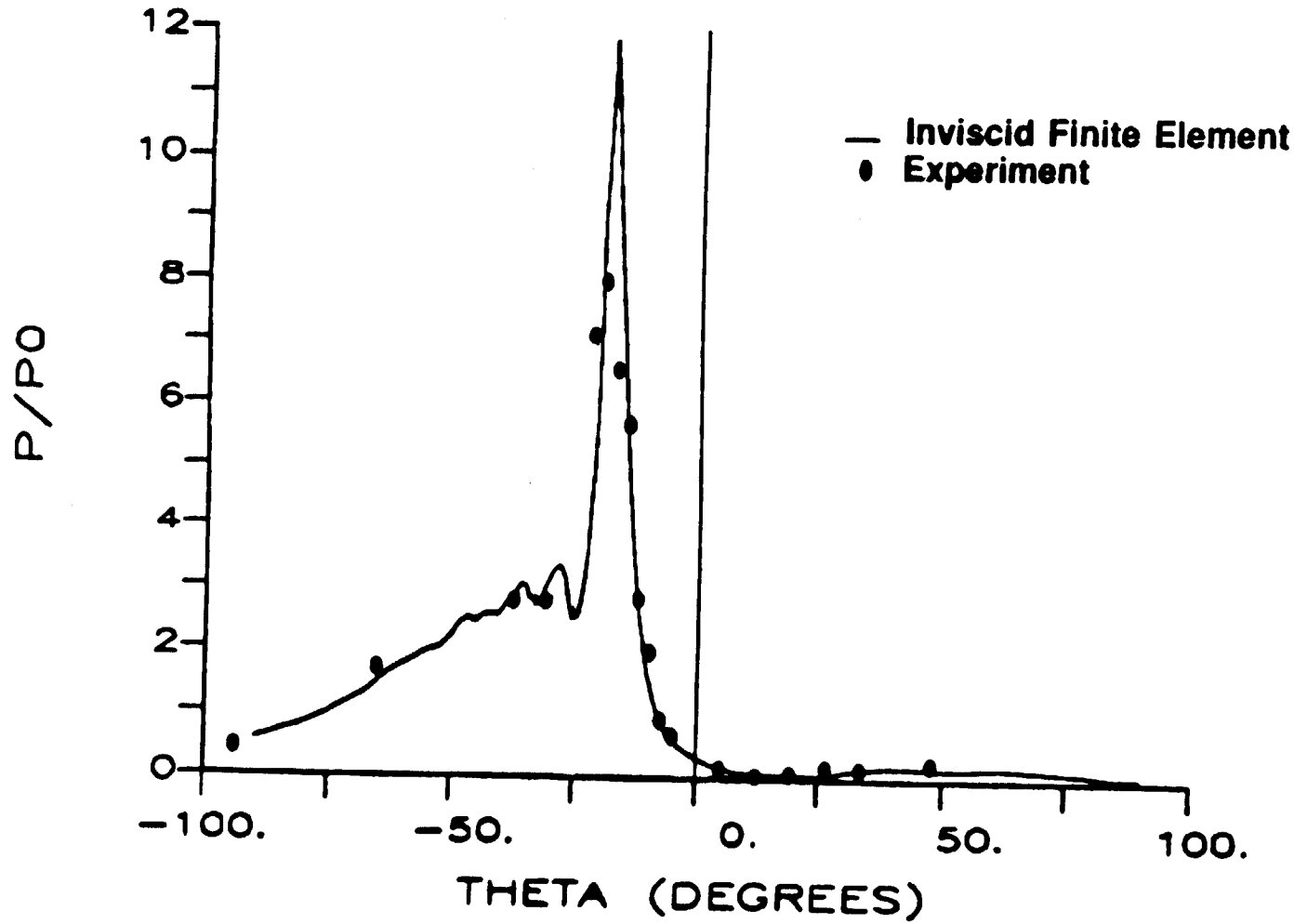
Second

Third



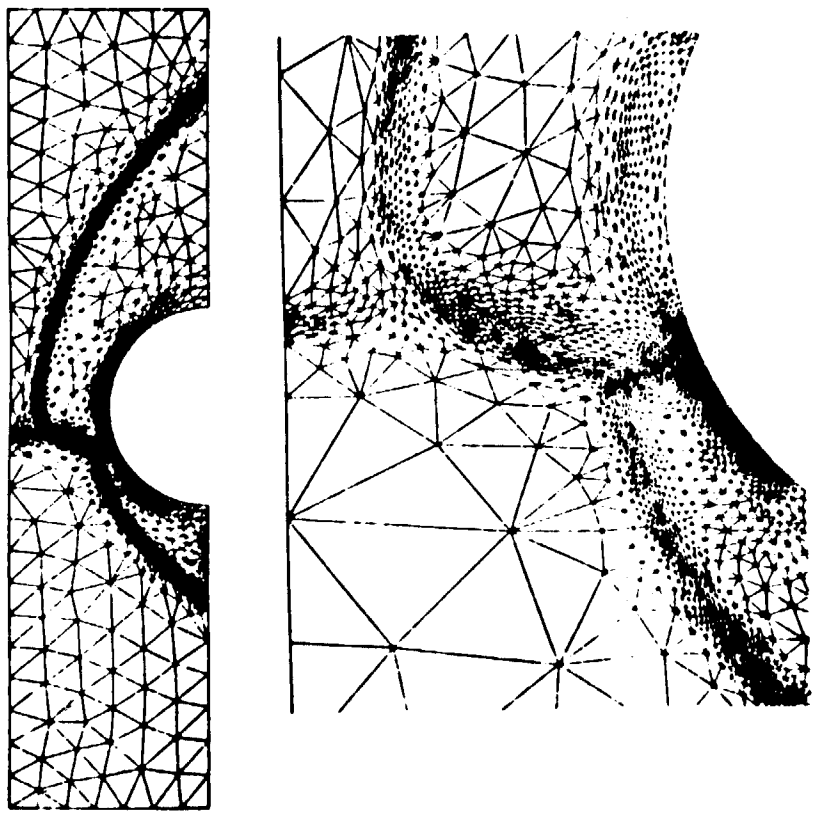
Final

COMPARISON OF MACH 8 PRESSURE DISTRIBUTION

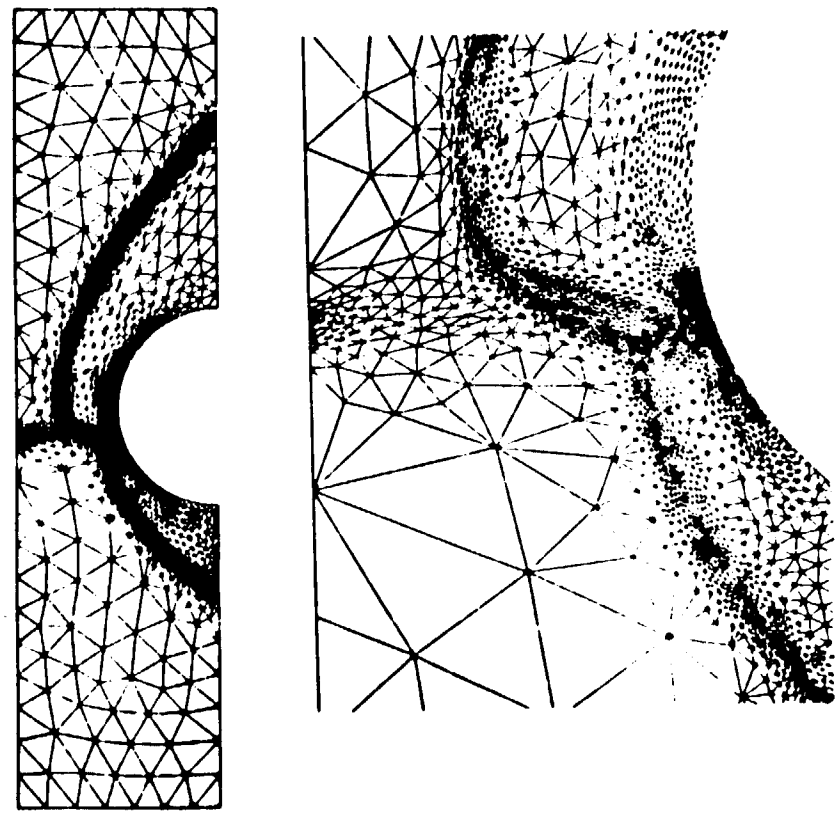


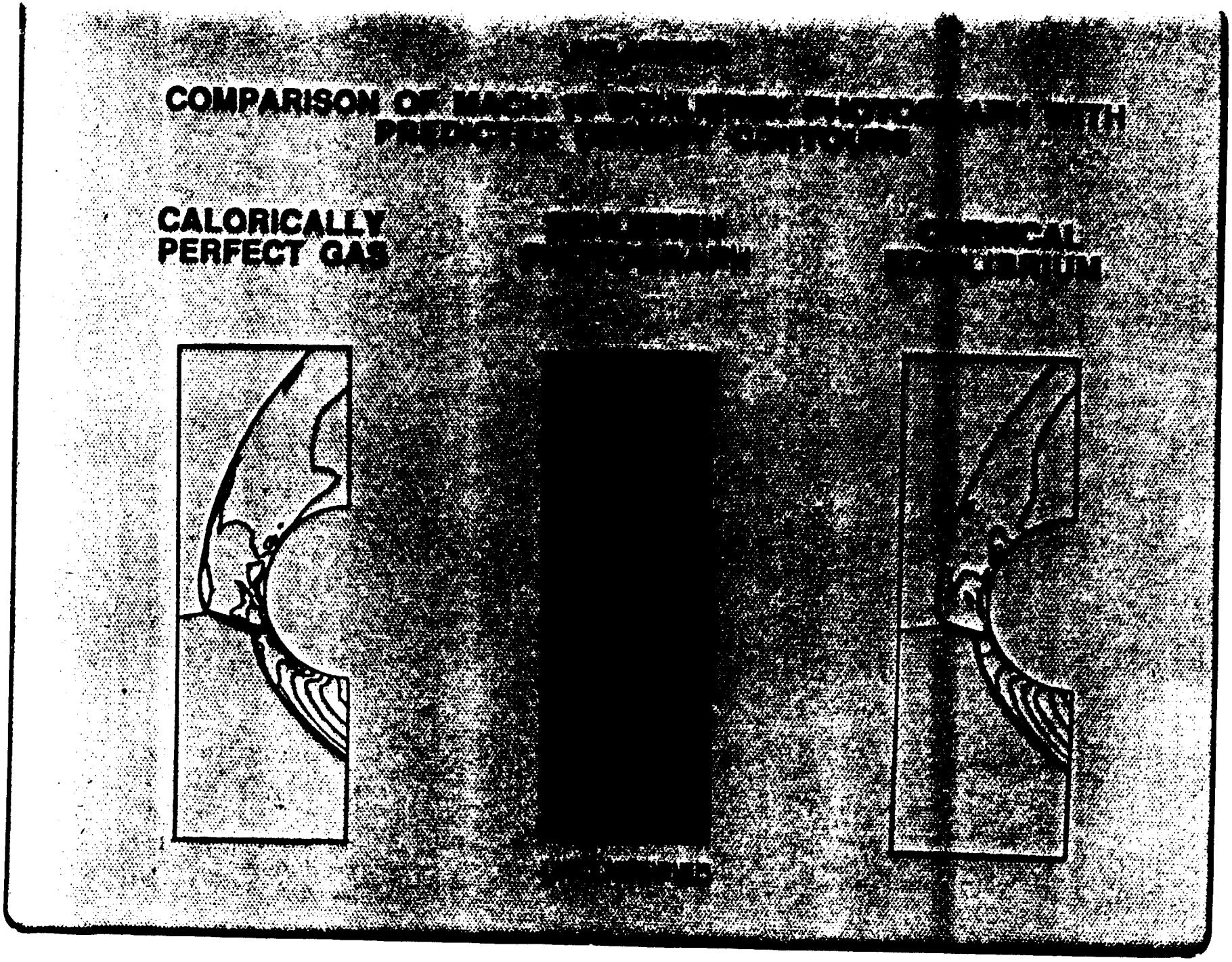
ADAPTIVE GRID FOR MACH 16 INVISCID FINITE ELEMENT ANALYSIS

PERFECT GAS



CHEMICAL EQUILIBRIUM





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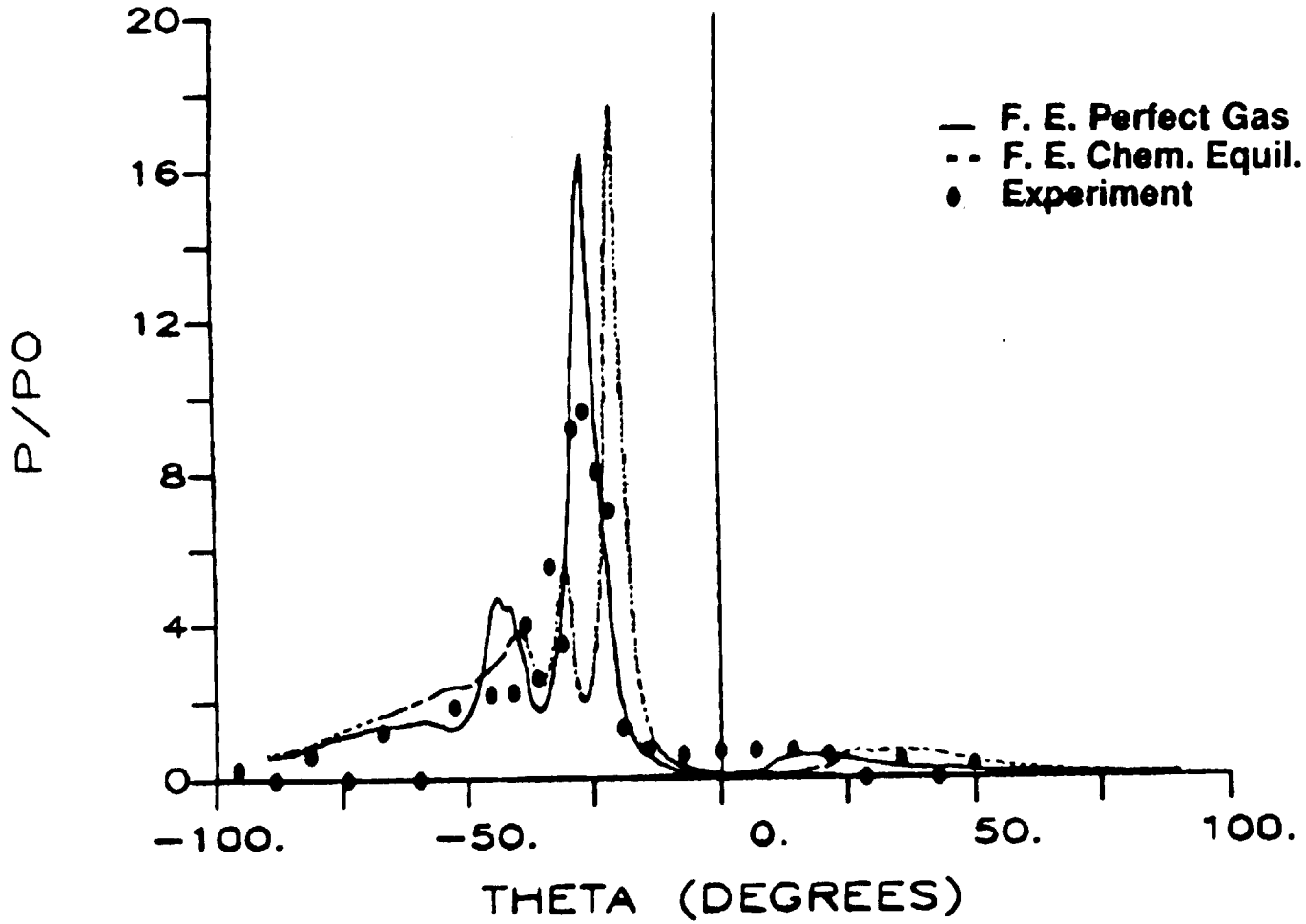
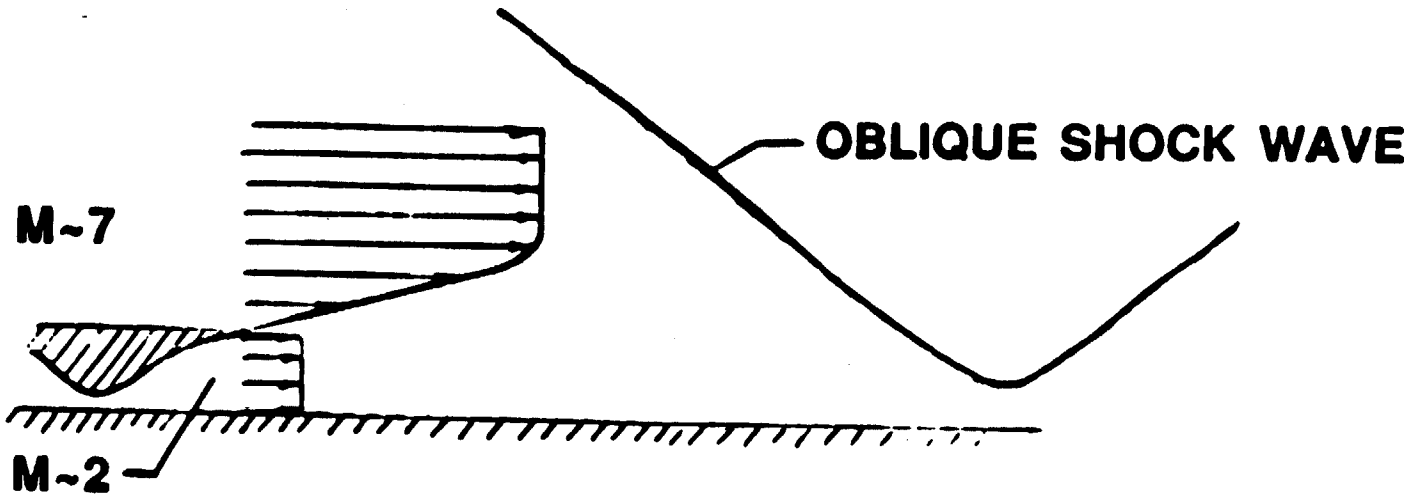
COMPARISON OF MACH 16 PRESSURE DISTRIBUTION



MASS ADDITION STUDIES



OBJECTIVES

- COOLING EFFECTIVENESS
- THRUST AUGMENTATION
- DRAG
- SHOCK WAVE INTERFERENCE
- LOCAL COMBUSTION
- COOLANT
- GEOMETRIC EFFECTS

MEASUREMENTS

- PROFILE
- SURFACE
- SCHLIEREN
- HOLOGRAPHY
- GAS SAMPLE

SUMMARY OF PLANNED INTERFERENCE HEATING STUDIES

- LEADING EDGES
  - 0°, 15°, & 30° SWEEP
  - 0°, 30°, & 30° YAW
  - MACH 6 TO 19
  - REYNOLDS NO. 0.4 TO 5 X 10^6/FT
- SUPERSONIC FILM COOLING
- TRANSPIRATION FILM COOLING
- AXIAL CORNER
  - SHOCK WAVE INTERFERENCE
  - AXIAL GAP WITH/WITHOUT PURGE GAS
- COMPRESSION CORNER
  - SPANWISE AND CHORDWISE GAPS

VALIDATION OF COMPUTATIONAL AEROELASTICITY

Woodrow Whitlow, Jr.
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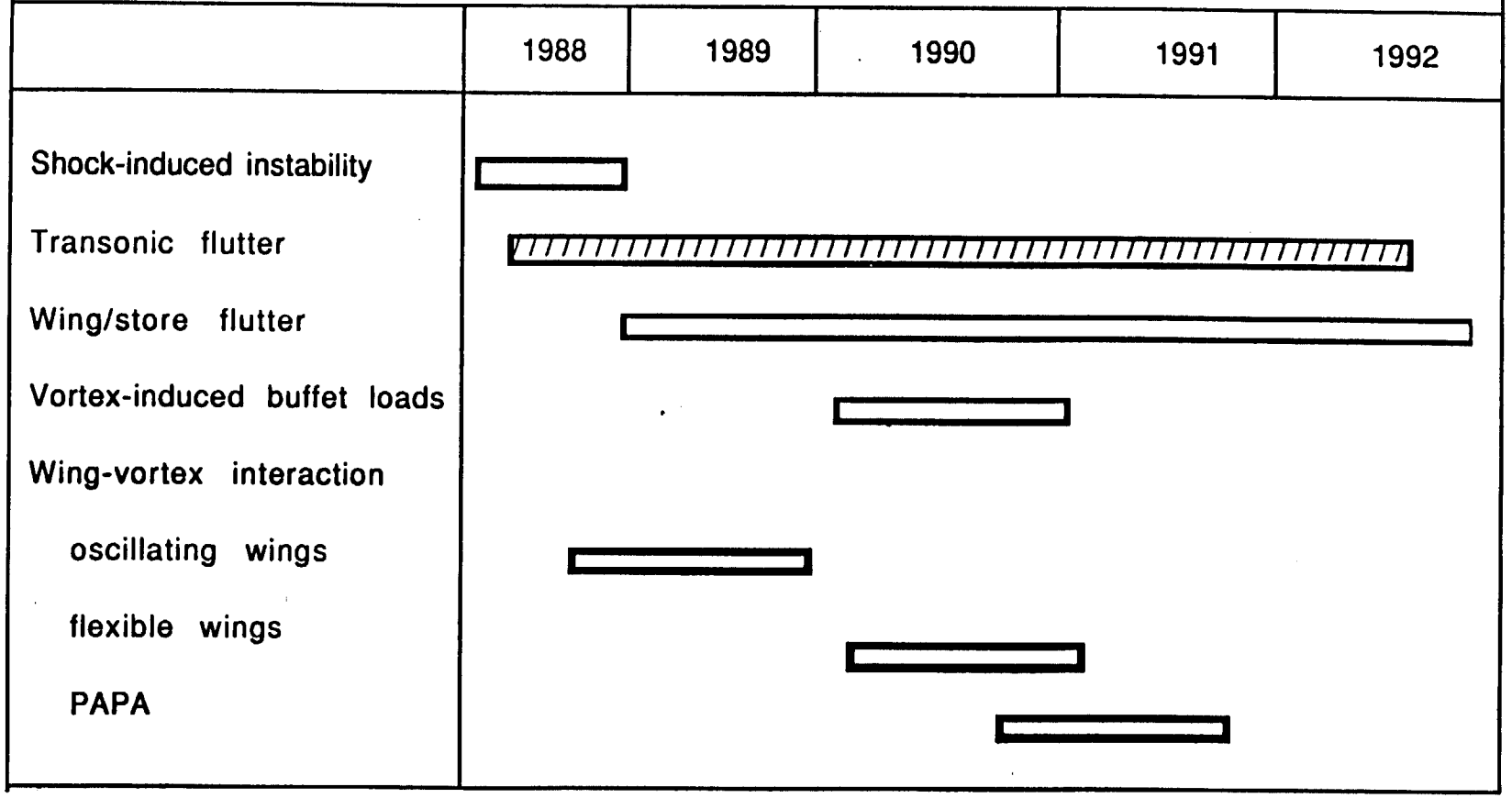
Presented at NASA Workshop on CFD Validation
NASA Ames Research Center
Moffett Field, CA 94035
July 14-16, 1987

N92-70934

BENCHMARK AEROELASTIC MODELS PROGRAM

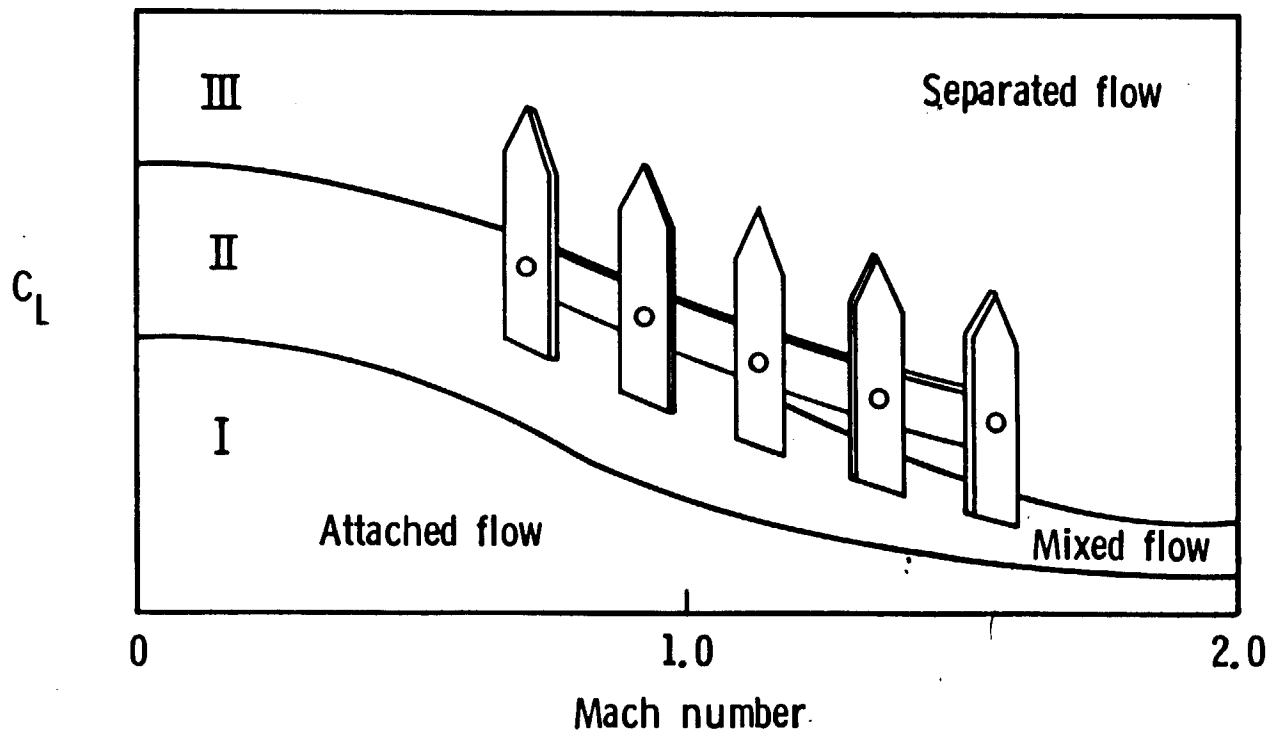
- **MOTIVATION**
  - DESIGN REQUIREMENTS FOR CURRENT AND FUTURE AIRCRAFT CALL FOR SIGNIFICANT IMPROVEMENTS IN COMPUTATIONAL METHODS FOR PREDICTING AEROELASTIC RESPONSE
  - THESE COMPUTATIONAL METHODS MUST BE VALIDATED BY COMPARISON WITH APPROPRIATE EXPERIMENTAL DATA
- **OBJECTIVE**
  - OBTAIN DATA FOR VALIDATION OF COMPUTATIONAL AEROELASTICITY COMPUTER CODES
- **METHOD**
  - TEST BENCHMARK AEROELASTIC MODELS TO ACQUIRE DATA FOR ASSESSING THE CAPABILITY TO PREDICT AEROELASTIC RESPONSE

BENCHMARK AEROELASTIC MODEL PROGRAM

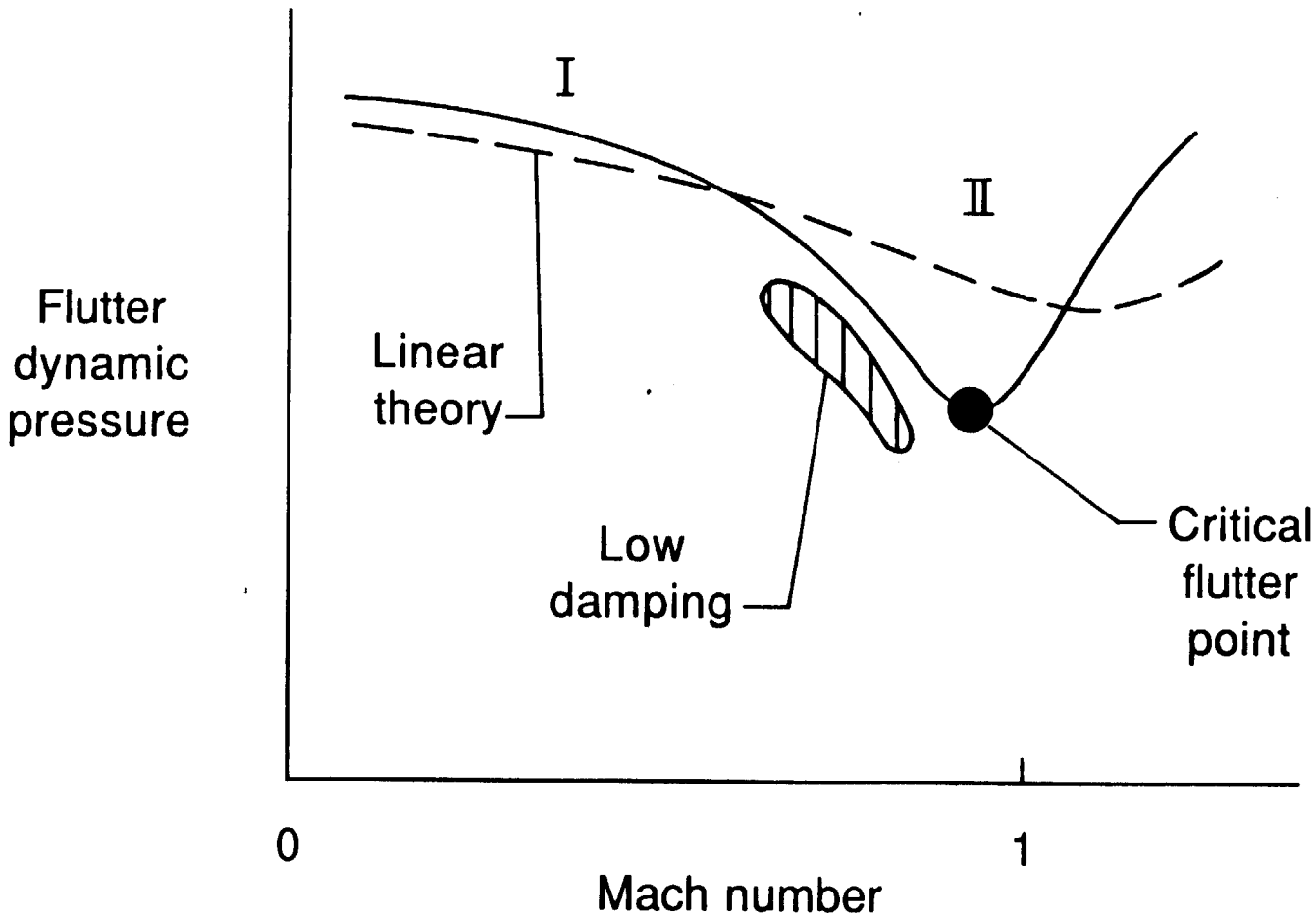


CHARACTERISTICS OF ATTACHED AND SEPARATED FLOW FOR COMPLETE AIRCRAFT

(After Bradley, 1981)



FEATURES OF TRANSONIC FLUTTER



BENCHMARK TRANSONIC FLUTTER MODEL PROGRAM

- **MOTIVATION:**
  - THE CRITICAL MINIMUM IN THE FLUTTER BOUNDARY OCCURS AT TRANSONIC SPEEDS AS FLOW IS TRANSITIONING FROM ATTACHED TO SEPARATED CONDITIONS
  - SUBCRITICAL RESPONSE AND FLUTTER DATA FOR A HIGHLY DEFINED CLEAN-WING MODEL ARE REQUIRED FOR CODE VALIDATION

- **OBJECTIVE:**
  - DETERMINE TRANSONIC FLUTTER BOUNDARY IN TDT FOR A HIGHLY DEFINED AEROELASTIC MODEL

- **METHOD:**
  - BUILD A TRANSONIC FLUTTER MODEL
  - ADEQUATELY DEFINE STRUCTURAL DYNAMIC, MASS, AND SURFACE GEOMETRY TO ALLOW COMPUTATIONAL CODE VALIDATION
  - TEST MODEL IN THE TDT TO DETERMINE:
    - Subcritical response and "hard" flutter boundary
    - Effects of loading conditions on flutter characteristics

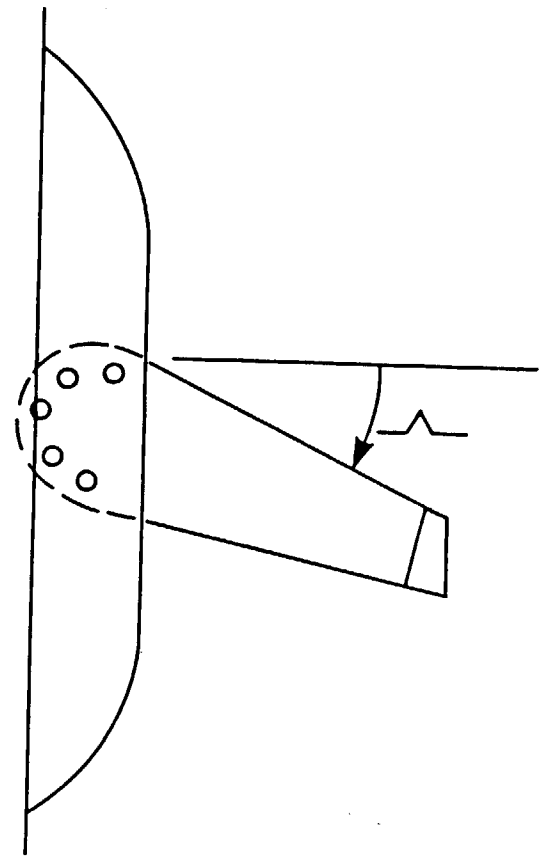
- **CODE VALIDATION:**
  - CAP-TSD (WITH INTERACTED BOUNDARY LAYER)
  - CFL3D EULER/NAVIER-STOKES CODE

- **COST:**

- DESIGN	$150K
- FABRICATION & INSTRUMENTATION	450K
- TOTAL	$600K

BENCHMARK TRANSONIC FLUTTER MODEL

- SWEPT, TAPERED WING WITH ADVANCED SYMMETRIC AIRFOIL SECTION
  - ASPECT RATIO = 7
  - THICKNESS RATIO = 10% - 14%
  - ADJUSTABLE SWEEP (SMALL CHANGES)
  - INTERCHANGEABLE WING TIPS (INCLUDING WINGLETS)



- STRUCTURAL DYNAMIC, MASS AND SURFACE GEOMETRY TO BE ADEQUATELY DEFINED TO ALLOW COMPUTATIONAL CODE VALIDATION

BENCHMARK TRANSONIC FLUTTER MODEL TESTING

FACILITIES

- TRANSONIC DYNAMICS TUNNEL (TDT)
  - 16' X 16' TEST SECTION
  - $M \leq 1.2$, $q \leq 500$ psf
  - WALL, STING, AND CABLE MOUNTS AVAILABLE

INSTRUMENTATION

- ACCELEROMETERS, STRAIN GAGES, UNSTEADY PRESSURES
- LASER LIGHT SHEET WITH HIGH-VOLUME VAPOR GENERATOR

BENCHMARK TRANSONIC FLUTTER MODEL (MEASUREMENTS)

- **WING SURFACE MEASUREMENTS**
  - UNSTEADY PRESSURES
  - STRAIN GAUGES, ACCELEROMETERS
  - STATIC WING DEFORMATIONS

- **MEASURE FLUTTER POINT**
  - NEUTRAL STABILITY IS A SENSITIVE TEST OF THE CODE
  - ACCURATE PREDICTION OF FLUTTER IS A VALIDATION OF THE CODE
  - MEASURE ACCURACY OF PREDICTING FLUTTER MACH NUMBER AND DYNAMIC PRESSURE

- **FLOW FIELD MEASUREMENTS - NONE**
  - INTRUSIVE MEASURING DEVICES CANNOT BE PLACED NEAR THE WING
  - NONINTRUSIVE POINT MEASUREMENTS (LV) INAPPROPRIATE
    - Safety
    - Phase coherence of measured data
  - GLOBAL VELOCIMETRY AND PARTICLE IMAGING APPLICABLE BUT NOT MATURE

- **FLOW VISUALIZATION**
  - LASER LIGHT SHEET WITH VAPOR GENERATOR

CODES FOR COMPUTATIONAL AEROELASTICITY VALIDATION

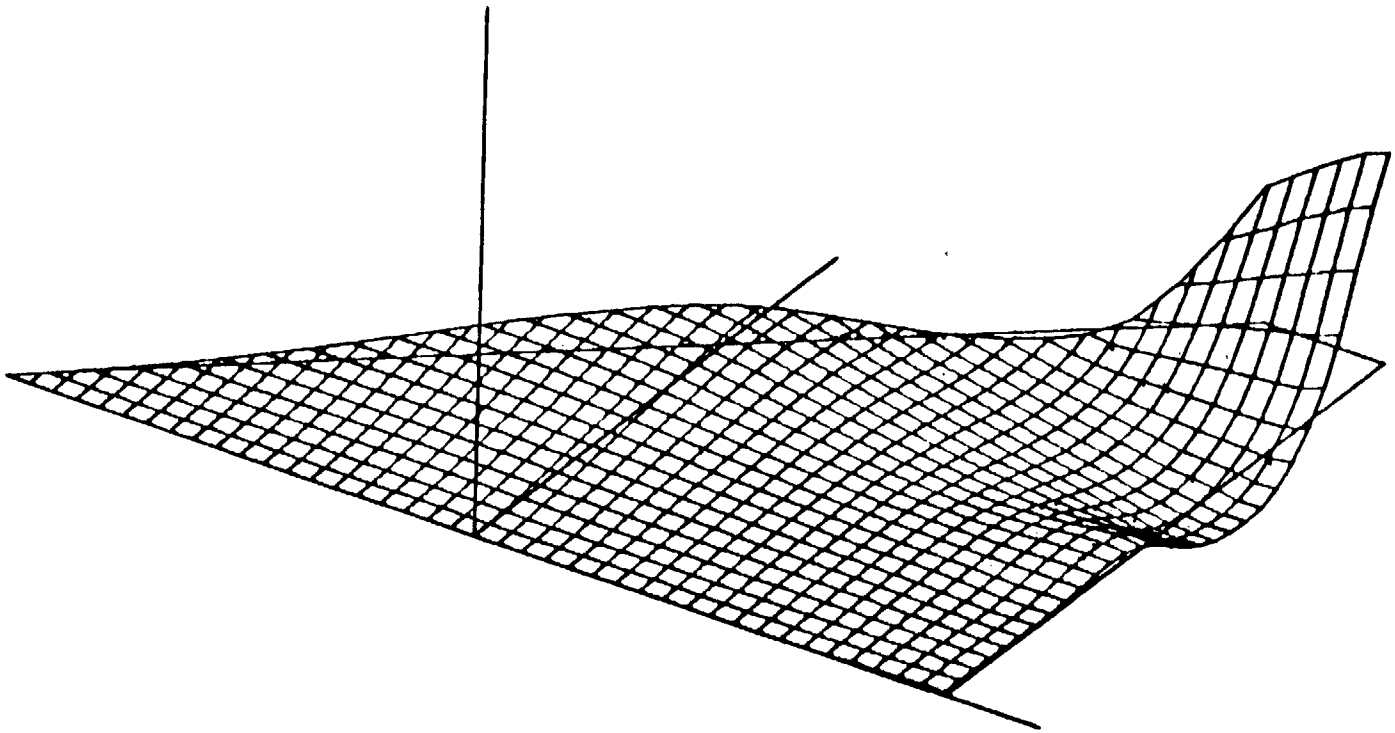
- **CAP-TSD WITH INTERACTED BOUNDARY LAYER**
  - 3-D TRANSONIC SMALL DISTURBANCE CODE
  - COMPLETE VEHICLE CONFIGURATIONS
  - APPROXIMATE FACTORIZATION ALGORITHM

- **CFL3D**
  - 3-D EULER/NAVIER-STOKES CODE
  - WING/BODY CONFIGURATIONS
  - UPWIND DIFFERENCING WITH FLUX-SPLITTING

- **NEED TO CALCULATE INTEGRATED EFFECTS OVER ENTIRE WING**

CODES FOR COMPUTATIONAL AEROELASTICITY VALIDATION

- FOR BODY-FITTED GRIDS, HAVE TO MODEL MOVING GRIDS AND MODE SHAPES



- LARGEST DEFORMATIONS AT WING TIP

CONCLUSIONS

- PRESENTED A PROGRAM TO VALIDATE TRANSONIC FLUTTER PREDICTION METHODS

- MUST MEASURE FLUTTER OF A HIGHLY DEFINED MODEL TO VALIDATE CODES
  - ACCURATE PREDICTION OF FLUTTER CONSTITUTES CODE VALIDATION

- PROPOSED CONSTRUCTION AND TEST OF A HIGHLY DEFINED FLUTTER MODEL
  - SWEPT, TAPERED WING WITH ADVANCED SYMMETRIC AIRFOIL SECTION
  - ASPECT RATIO = 7
  - THICKNESS RATIO = 10% - 14%
  - ADJUSTABLE SWEEP
  - COST:

DESIGN	$150K
FABRICATION AND INSTRUMENTATION	450K
TOTAL	600K

  - TEST IN LANGLEY TDT

- INTRUSIVE FLOW FIELD MEASUREMENTS NOT APPROPRIATE

OVERVIEW OF CFD VALIDATION EXPERIMENTS

NASA CFD VALIDATION WORKSHOP

JULY 14-16, 1987

LOUIS A. POVINELLI
DEPUTY CHIEF, INTERNAL FLUID MECHANICS DIVISION
LEWIS RESEARCH CENTER

N92-70935

CLASSES OF VALIDATION EXPERIMENTS

- FUNDAMENTAL PHYSICS EXPERIMENTS
  - ISOLATED PHENOMENA
  - SIMPLE SHAPES
  - NON-ROTATING
  - NOT COMPONENT SPECIFIC
- APPLIED PHYSICS EXPERIMENTS
  - MULTIPLE PHENOMENA
  - COMPLEX SHAPES
  - ROTATING
  - COMPONENT SPECIFIC
  - END WALL, CLEARANCE, VORTEX FLOWS

PHYSICAL FLOW PHENOMENA

FUNDAMENTAL PHYSICS

- o SHOCK WAVES
- o BOUNDARY LAYERS
- o SECONDARY FLOW
- o JET INJECTION
- o FLOW EXCITATION
- o HEAT TRANSFER
- o KINETICS

APPLIED PHYSICS

- o INLET SHOCK STRUCTURE
- o TURBOMACHINERY END WALL FLOWS
- o TURBINE BLADE VORTEX FLOW
- o FUEL PENETRATION IN COMBUSTOR
- o NOZZLE MIXING
- o LEADING EDGE COOLING
- o REACTING SHEAR LAYERS

FUNDAMENTAL PHYSICS

BOUNDARY LAYER TUNNEL

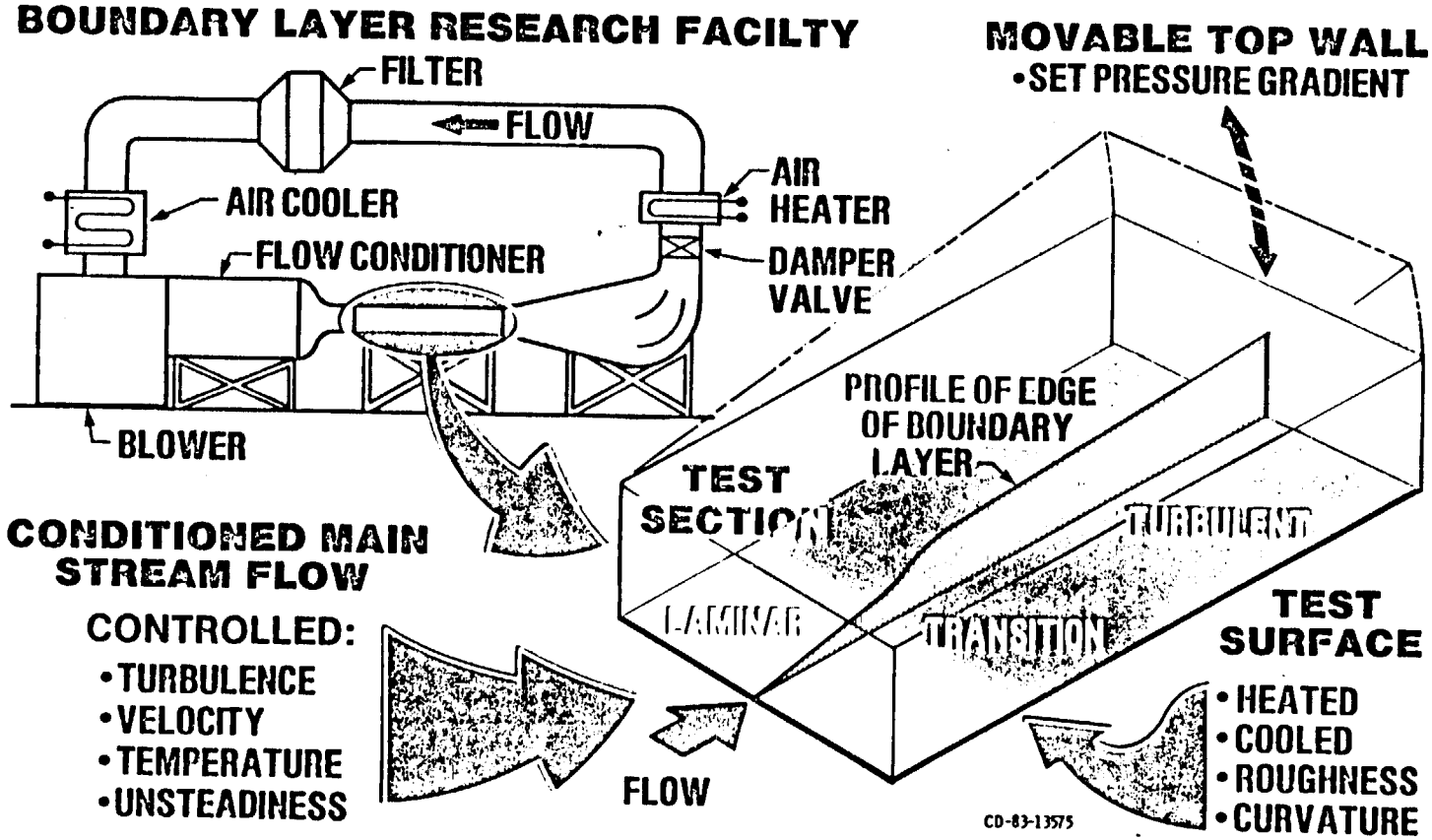
FLOW PHYSICS	MEASUREMENTS
o BOUNDARY LAYERS, ONSET AND TRANSITION MECHANISMS	TURBULENCE SCALES AND INTENSITIES
o EFFECT OF HEAT TRANSFER ON TRANSITION	INTERMITTANCY
o HEAT TRANSFER AND SKIN FRICTION DISTRIBUTION WITHIN TRANSITION REGION	SKIN FRICTION, REYNOLD'S STRESSES

NASA
C-83-0452

BOUNDARY LAYER RESEARCH

NASA

DEVELOP ABILITY TO ACCURATELY PREDICT HEAT TRANSFER BETWEEN A GAS AND A SURFACE UNDER GAS TURBINE ENGINE CONDITIONS



APPLIED PHYSICS

CENTRIFUGAL COMPRESSOR

FLOW PHYSICS

SECONDARY FLOWS

HUB AND TIP CORNER VORTICES

TIP CLEARANCE FLOW

UNSTEADY DIFFUSER FLOW

MEASUREMENTS

ROTOR AND DIFFUSER PRESSURES AND TEMPERATURES

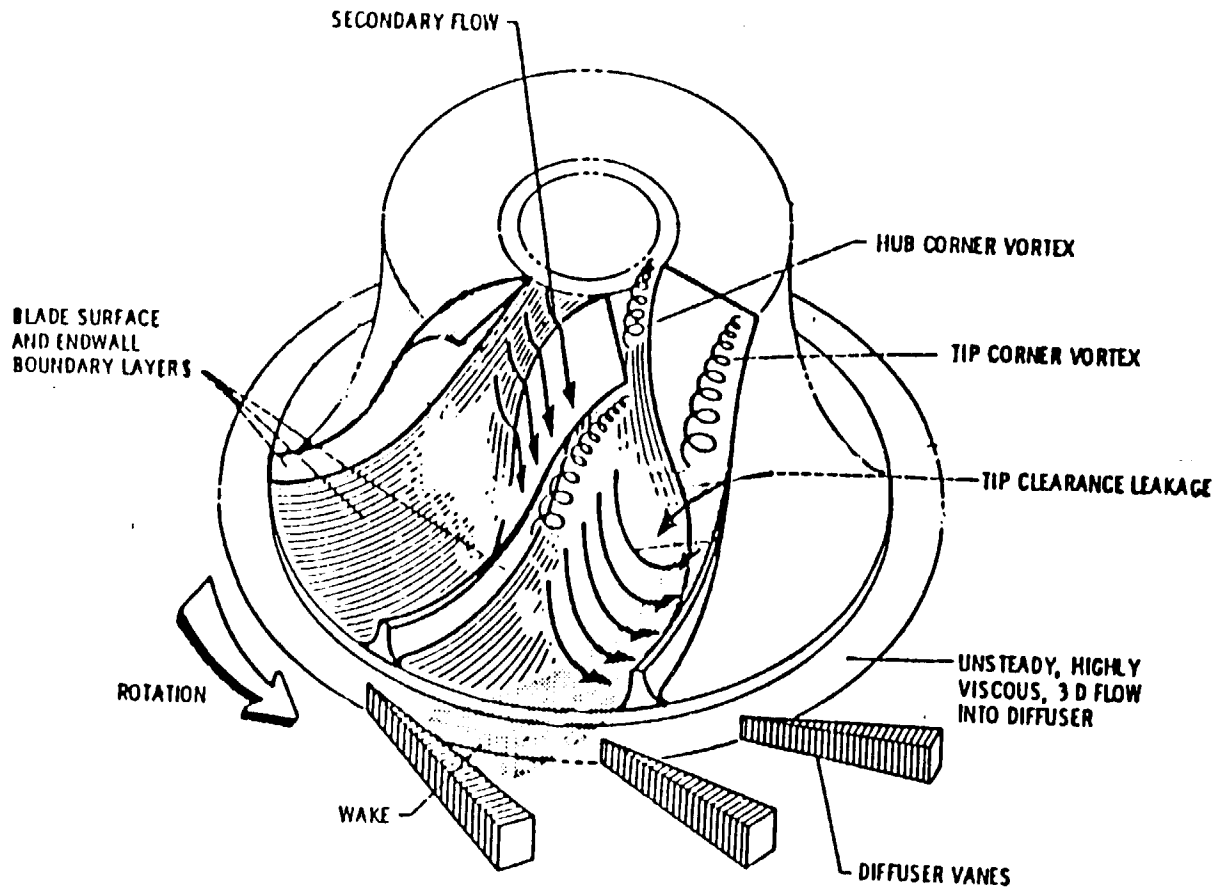
LASER VELOCITY MEASUREMENTS

HOT WIRE MEASUREMENTS

ROTOR DYNAMIC PRESSURES

SURFACE FLOW AND STREAMLINE VISUALIZATION

CENTRIFUGAL COMPRESSOR FLOW PHENOMENA



National Aeronautics and Space Administration

Lewis Research Center

INTERNAL FLUID MECHANICS DIVISION

NASA

TURBOMACHINERY

EXPERIMENT	UNDERSTAND FLOW PHYSICS	DEVELOP PHYSCIAL MODELS	CFD CALIBRATE	CFD VALIDATE
o AXIAL COMPRESSORS	✓		✓	✓
- ROTOR 35 - RADIAL VELOCITY COMPON.			✓	✓
- ROTOR 37 - R/S INTERACTION (CLOSE SPACING)				✓
- LOW SPEED LINEAR CASCADE		✓	✓	✓
- LOW SPEED AXIAL (MULTISTAGE)		✓	✓	
o CENTRIFUGAL COMPRESSORS				✓
- LOW SPEED CENTRIFUGAL COMPRESSOR			✓	
o TURBINES AERODYNAMICS				
- ANNULAR CASCADE - TRANSONIC M; E^3 VANES			✓	✓
- ASME CFD PREDICTION			✓	✓
- TURBINE BLADE ROW INTERACTION			✓	✓
o TURBINE HEAT TRANSFER				
- LEADING EDGE STAGNATION REGION		✓		
- CASCADE ENDWALL		✓	✓	✓
- COMP. TUNNEL INTERSECTING SURFACE		✓		
- HIGH REYNOLDS NUMBER AIRFOIL			✓	
- BOUNDARY LAYER TRANSITION		✓		
- ROTOR WAKE		✓		
- LIGHT PISTON TUNNEL				
- HIGH TEMPERATURE HEAT FLUX (FCRI 2)				

TUBOMACHINERY CFD VALIDATION

CODE AND CRITICAL MODELS REQUIRING VALIDATION		EXPERIMENTAL PROGRAM ELEMENTS
CFD CODE BY CLASS	FLOW PHYSICS MODELS	
STEADY EULER	END-WALL B. LAYER BLADE SURFACE B. LAYER SHOCK B. LAYER INT. TURBULENCE	HI-SPEED TURBO. LO-SPEED TURBO. 2-D CASCADE SHOCK B. LAYER INT.
STEADY NAVIER-STOKES	TURBULENCE B. LAYER TRANSITION	2-D CASCADE LO-SPEED CENTRIF. LO-SPEED B. LAYER 3D-HEAT TRANSFER LO-SPEED AXIAL TURBO.
PASSAGE-AVERAGE NAVIER-STOKES	TURBULENCE OTHER CLOSURE MODELS	LO-SPEED MULTISTAGE HI-SPEED MULTISTAGE
UNSTEADY NAVIER-STOKES (ROTOR/STATOR)	TURBULENCE B. LAYER TRANSITION	LO-SPEED TURBO. HI-SPEED TURBO.

INLETS, DUCTS & NOZZLES

EXPERIMENT	UNDERSTAND FLOW PHYSICS	DEVELOP PHYSICAL MODELS	CFD CALIBRATE	CFD VALIDATE
o DUCTS				
- SHOCK/BL INTERACTION	✓		✓	✓
- TRANSITION DUCT (AERO. & HEAT TRANS.)	✓			✓
- OUT-OF-PLANE BENDS (G)	✓		✓	✓
- VORTEX GENERATORS	✓	✓		✓
o AERODYNAMIC EXCITATION				
- FREE SHEAR LAYER MIXING	✓		✓	
- AIRFOIL (BLADING) FLOW CONTROL	✓		✓	
- EXCITATION DEVICES	✓		✓	

INLET, DUCT AND NOZZLE CFD VALIDATION

CODE AND CRITICAL MODELS REQUIRING VALIDATION		
CFD CODES BY CLASS	CRITICAL FLOW PHYSICS MODELS	EXPERIMENTAL PROGRAM ELEMENTS
SUBSONIC 3-D PNS	TURBULENCE SEPARATION (FLARE APPROX.) VORTEX GENERATOR	TRANSITION DUCT (AERO & OFFSET DUCT THERMAL) VORTEX GENERATOR
3-D SUPERSONIC/ HYPERSONIC PNS	TURBULENCE SEPARATION (FLARE APPROX.) REAL GAS EFFECTS B. L. BLEED B. L. TRANSITION	B. L. BLEED SHOCK/B. L. INTERACTION INLET/DUCT/NOZZLE COMPON. HIGH TEMP. REACTING FLOW
3-D UNSTEADY NS	TURBULENCE REAL GAS EFFECTS B. L. TRANSITION	ALL OF THE ABOVE PLUS: SEPARATED FLOW PHYSICS SHOCK STANDOFF STAGNATION POINT HT. TRANS. NONORTHOGONAL SURFACE

CHEMICAL REACTING FLOWS

EXPERIMENT	UNDERSTAND FLOW PHYSICS	DEVELOP PHYSICAL MODELS	CFD CALIBRATE	CFD VALIDATE
2-PHASE FLOW	✓			✓
FLUID SPRAY STUDIES	✓			
LOW TEMPERATURE HEAT TRANSFER	✓			
FUEL SPRAY CHARACTERIZATION	✓			✓
PREMIX FLAME STUDIES	✓			
DIFFUSION FLAME STUDIES	✓			
RICH CATALYTIC COMBUSTION	✓			
CHEMICAL KINETICS STUDIES	✓	✓		
SOOT FORMATION	✓	✓		
PLANAR REACTING SHEAR LAYER	✓			✓
HIGH SPEED MIXING LAYER	✓			✓
SWIRLING FLOW INTERACTION	✓			✓
HOT GAS INGESTION	✓			✓
STRUCTURES IN SHEAR LAYERS	✓			
PREMIXED TURBULENT FLAME	✓			

CHEMICALLY REACTING FLOWS CFD VALIDATION

CODE AND CRITICAL MODELS REQUIRING VALIDATION		EXPERIMENTAL PROGRAM ELEMENTS
CFD CODES BY CLASS	CRITICAL FLOW PHYSICS MODELS	
STEADY NAVIER-STOKES	FUEL SPRAY TURBULENCE TURBULENCE/COMBUSTION CHEMICALS KINETICS INTERACTION RADIATION/SOOT FORMATION	MULTI-PHASE FLOW RESEARCH: PHASE INTERACTION
TIME ACCURATE NAVIER-STOKES	TURBULENCE TURBULENCE/COMBUSTION INTERACTION CHEMICAL KINETICS	PLANAR REACTING SHEAR LAYER: TURBULENCE/COMBUSTION INTERACTION BASIC COMBUSTION LAB: SOOT/RADIATION CHARACTERISTICS
DIRECT NUMERICAL SIMULATION	CHEMICAL KINETICS	SHOCK TUBE RESEARCH CHEMICAL KINETICS

VALIDATION EXPERIMENTS FOR HIGH SPEED SEPARATED FLOWS

NASA CFD VALIDATION WORKSHOP

JULY 14-16, 1987

WARREN R. HINGST
AERODYNAMICS BRANCH
INTERNAL FLUID MECHANICS DIVISION
LEWIS RESEARCH CENTER

RESEARCH DRIVERS

* AFFECTED FLOW COMPONENTS

  . INLETS
    SHOCK–B.L. INTERACTIONS
    CORNER FLOWS

  . TRANSITION DUCTS
    HIGH CURVATURE

* BENEFITS OF UNDERSTANING SEPARATIONS AND APPLYING CFD

  . OPTIMIZATION WEIGHT/PERFORMANCE

  . IMPROVE FLOW QUALITY

  . ELIMINATE UNSTEADY OPERATION

OBJECTIVES

* OBTAIN CFD VALIDATION DATA FOR SEPARATED HIGH SPEED FLOWS

* STUDY FLOW PHYSICS

NASA LEWIS 3D VISCOUS CODES

PEPSI

S--SUPERSONIC G--SUBSONIC
IMPLICIT 3D PNS

THREE DIMENSIONAL NAVIER-STOKES
NEGLECTING STREAMWISE DIFFUSION

- ENERGY EQUATION
- STREAMWISE MARCHING - IMPLICIT
- GRID CONCENTRATION
- TURBULENCE MODELS
- FLARE APPROXIMATION

PROTEUS

IMPLICIT 3D FULL NAVIER-STOKES
TEST-BED SOLVER

- 3D, TIME-MARCHING, COMPRESSIBLE
- GENERAL, NON-ORTHOGONAL COORDINATE SYSTEM
- LINEAR BLOCK IMPLICIT (LBI) SOLVER
- BALDWIN-LOMAX TURBULENCE MODEL
- ENERGY EQUATION, PERFECT GAS RELATIONSHIP

CODE VALIDATION OBJECTIVES

*PEPSI PNS CODES

- FLOW FIELD PROPERTIES
- TRANSPORT PROPERTIES
- PREDICTION OF INCIPIENT SEPARATION
- EXTENT OF SEPARATION
- APPLICABILITY FOR MASSIVE SEPARATION

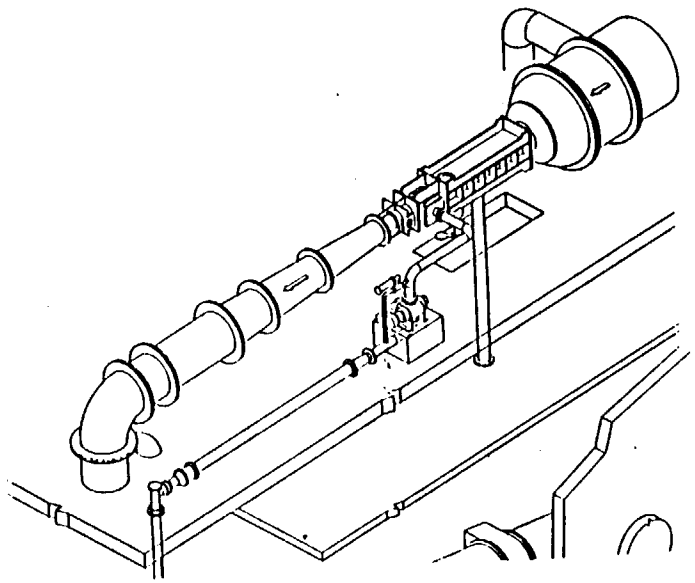
*PROTEUS N-S CODE

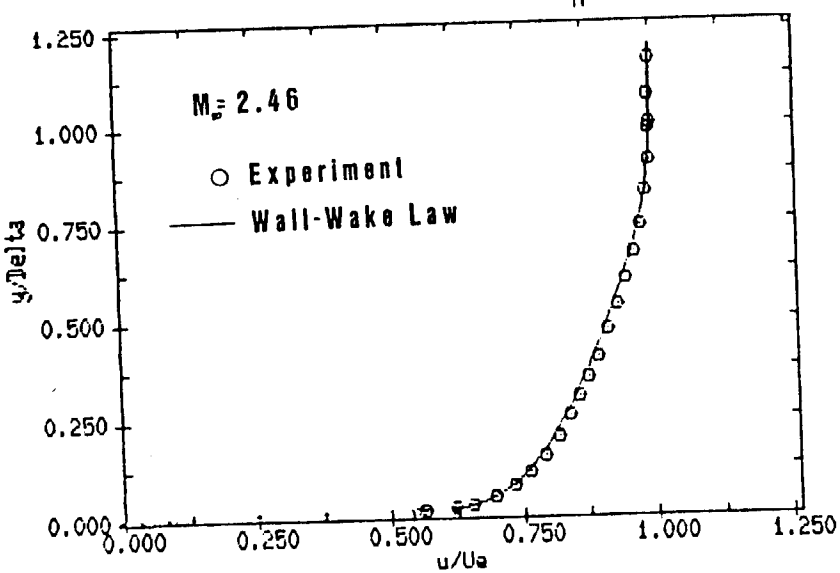
- FLOW FIELD PROPERTIES
- TRANSPORT PROPERTIES
- SEPARATED FLOW DETAILS
- PREDICTION OF INCIPIENT SEPARATION
- EXTENT OF SEPARATION

VALIDATION EXPERIMENTS

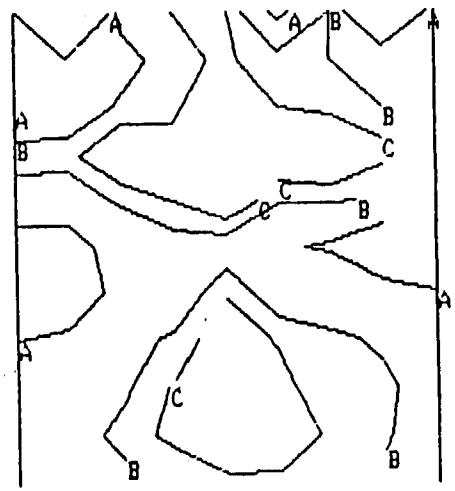
* IFM FACILITY AND 1X1 SUPERSONIC SWT
  - APPROPRIATE TEST CONDITIONS
  - HIGH QUALITY FLOW
* GENERATE CLEAN CONTROLLED SEPARATION
  - APPROPRIATE PHYSICS FOR APPICATION
  - ISOLATE FROM OTHER PHENOMENA
* OBTAIN CFD VALIDATION DATA WITH MIN OR NON-INTRUSIVE INSTRUMENTATION
  - MEAN FLOW MEASUREMENTS
    - LDA
    - PRESSURES
    - HOT-WIRE ANEMOMETRY
    - LASER INTERF. SKIN FRICTION
    - HEAT TRANSFER
  - TIME DEPENDENT
* VALIDATION PROCESS
  - DETAILED COMPARISONS
    - FLOW FIELD
    - TRANSPORT PROPERTIES
  - FEEDBACK TO EXPERIMENT
    - ADDITIONAL DATA
    - NEW TEST CONDITIONS

NASA LEWIS 1FT X 1FT SWT





Upstream Boundary Layer Survey

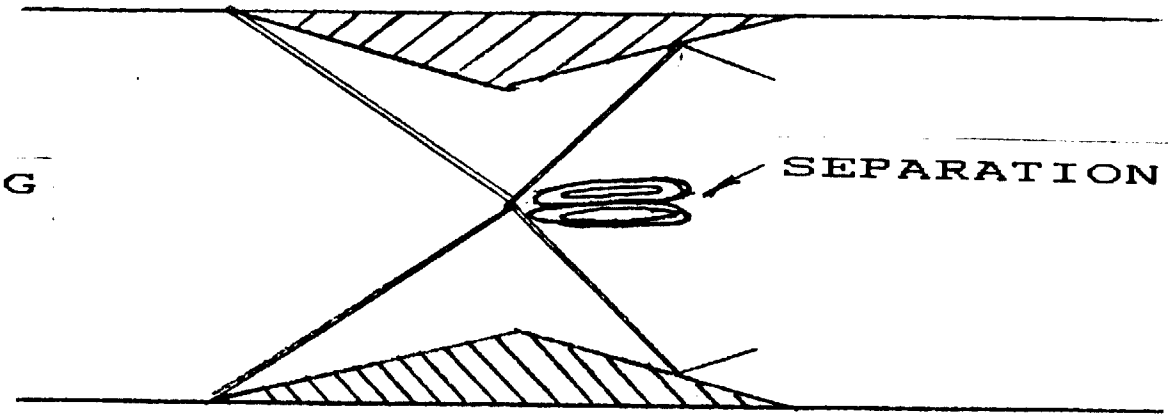


Mach No.
A -- 1.955
B -- 1.965
C -- 1.970

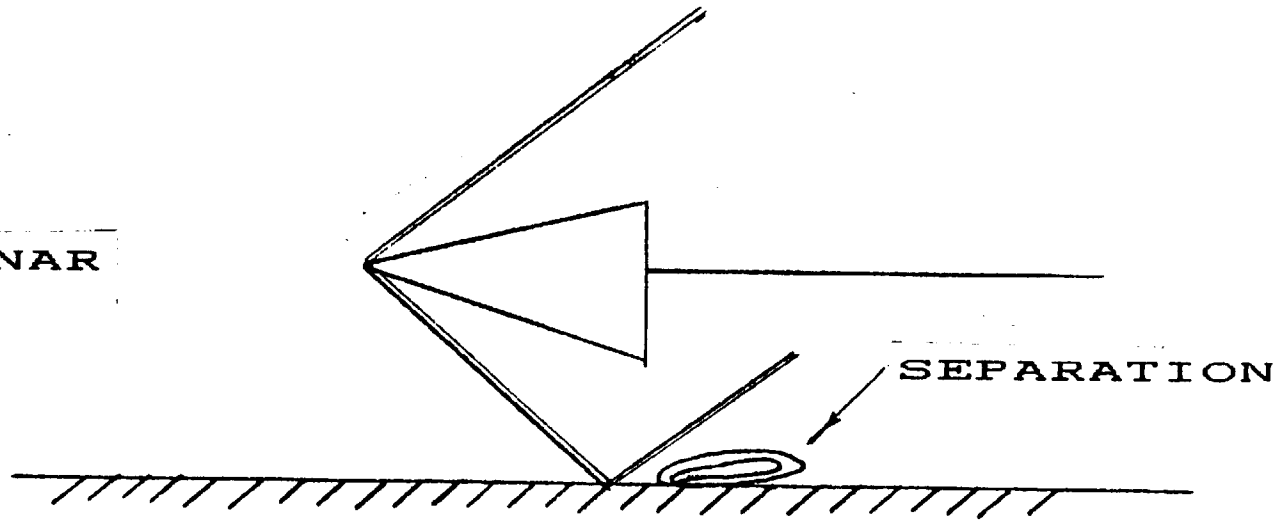
Freestream Cross-Plane Mach No. Contours

SEPARATION EXPERIMENTS FOR INLET FLOWS

INTERSECTING GLANCING SIDWALL SHOCK–B.L. INTERACTIONS

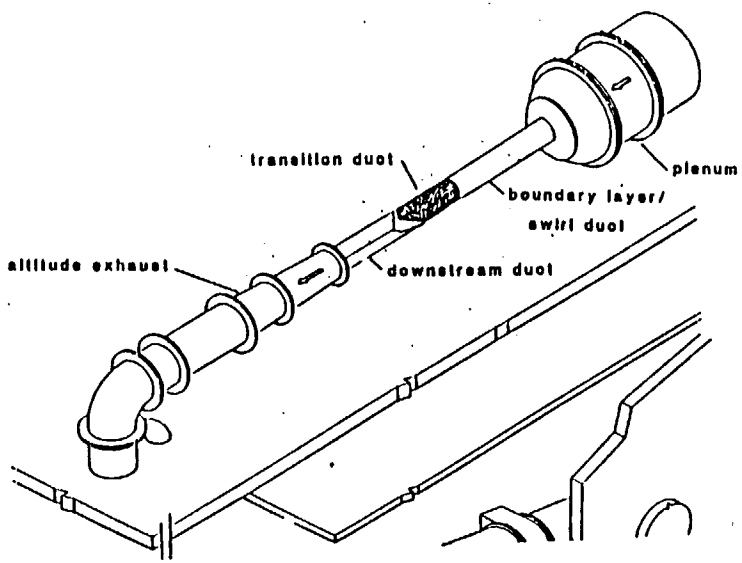


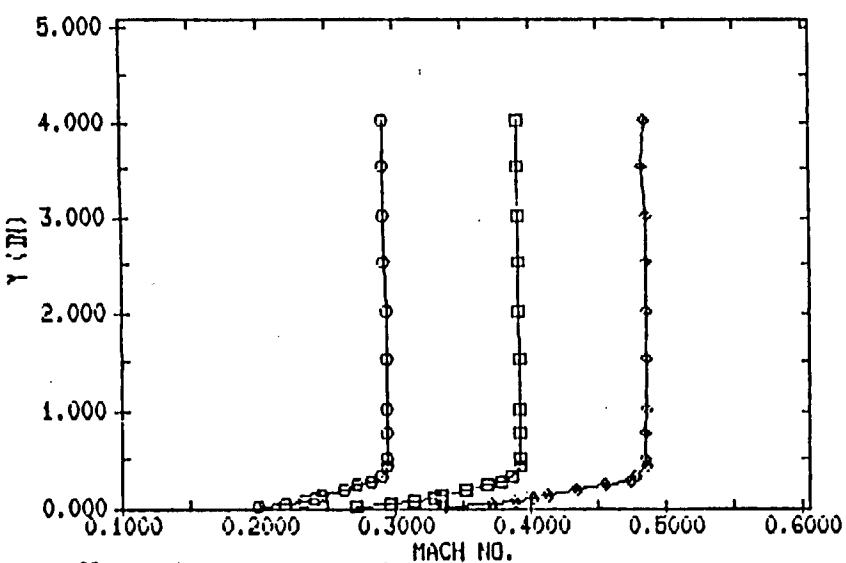
CONICAL SHOCK–PLANAR B.L. INTERACTION



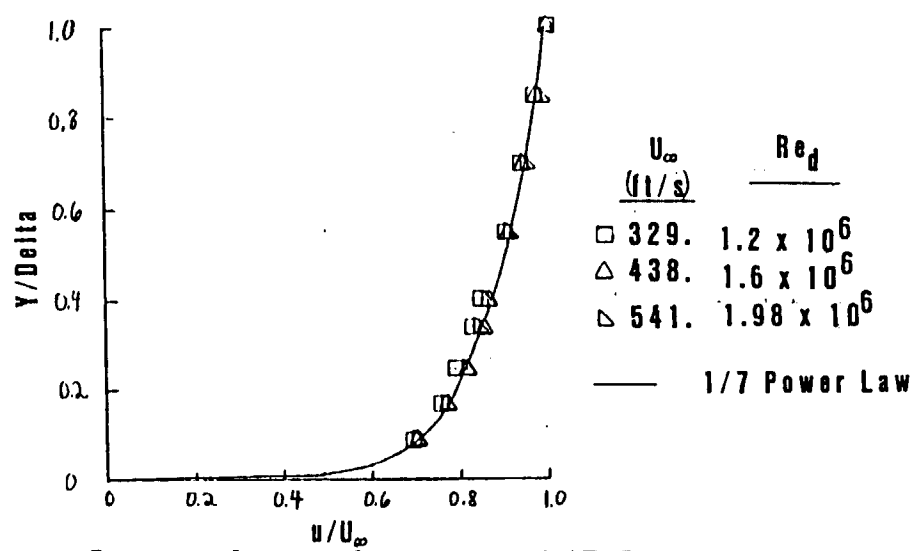
MACH NUMBER 1.3 TO 4.0
RN NUMBER 3 TO 8 M

NASA LEWIS INTERNAL FLUID MECHANICS FACILITY





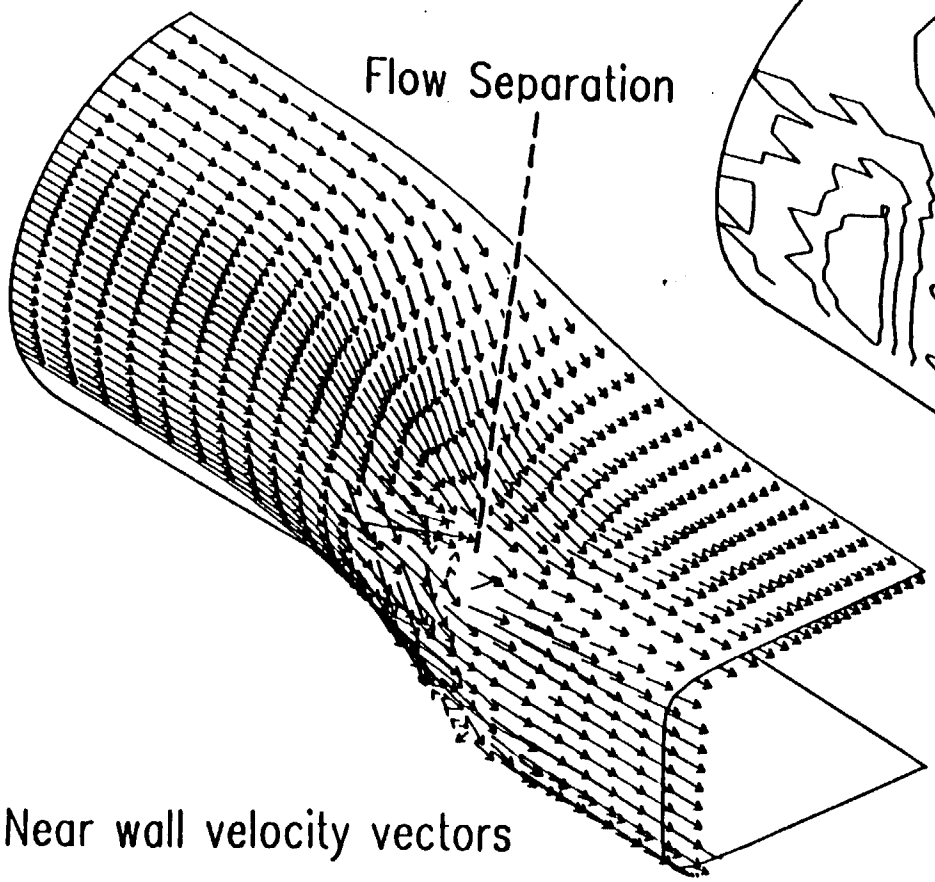
Upstream Boundary Layer Duct Survey



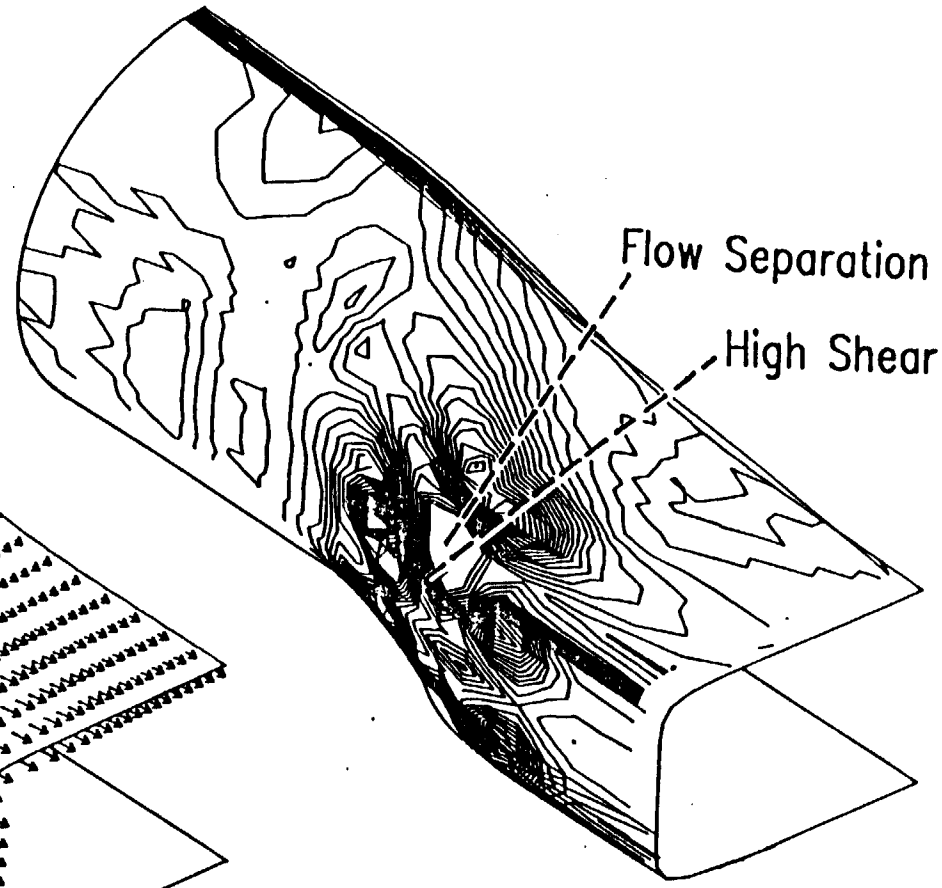
Comparison of Data to 1/7 Power Law

SEPARATION EXPERIMENTS FOR TRANSITION DUCT FLOWS

MACH NUMBER 0 TO .9
RN 4 M



Near wall velocity vectors



Surface shear stress signature

SUMMARY

* SEPARATION IMPORTANT FOR HIGH SPEED COMPONENT PERFORMANCE

*CONDUCT CFD VALIDATION EXPERIMENT IN QUALIFIED FACILITY

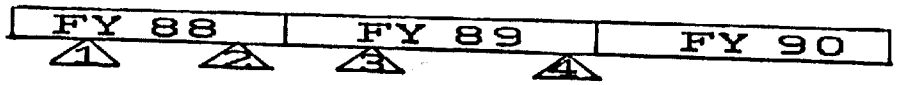
*OBTAIN CFD VALIDATION DATA AND STUDY FLOW PHYSICS

RESOURCES AND SCHEDULE

FUNDING— 75K /YR

MANPOWER— .75 MY/YR

SCHEDULE



1. START INITIAL SUPERSONIC TESTING
2. START SUBSONIC TESTING
3. PNS VALIDATON
4. PROTEUS VALIDATION

National Aeronautics and
Space Administration

Lewis Research Center

NASA

THREE DIMENSIONAL FLOWS IN MULTISTAGE COMPRESSORS

NASA CFD VALIDATION WORKSHOP

Ames Research Center

July 14-16, 1987

MICHAEL D. HATHAWAY

N92-70936

353.

PROGRAM MOTIVATION

CURRENT MULTI-STAGE TURBOMACHINERY DESIGN/ANALYSIS METHODS ARE BASED ON TIME-AVERAGED, AXISYMMETRIC REPRESENTATION OF FLOW FIELD

ACTUAL FLOW FIELD IS ASYMMETRIC AND UNSTEADY DUE TO BLADE ROW INTERACTIONS

REYNOLDS AVERAGED NAVIER-STOKES SOLVERS LIMITED TO SINGLE-STAGE MACHINES FOR EXISTING COMPUTERS

ADVANCED MULTI-STAGE COMPRESSORS WILL OPERATE FAR OFF-DESIGN FOR PORTIONS OF THE FLIGHT REGIME

PROGRAM OBJECTIVES

PROVIDE AN EXPERIMENTALLY VALIDATED AVERAGE-PASSAGE CALCULATION OF MULTISTAGE COMPRESSOR BLADE ROW INTERACTIONS

- DEVELOP A FUNDAMENTAL QUANTITATIVE UNDERSTANDING OF THE GENERATION OF BOTH STEADY AND UNSTEADY NONAXISYMMETRIC FLOWS, THEIR TRANSPORT AND DISSIPATION IN A MULTI-BLADE ROW TURBOMACHINERY ENVIRONMENT
- QUANTIFY THE EFFECT OF NONAXISYMMETRIC FLOWS ON THE PERFORMANCE AND DURABILITY OF TURBOMACHINERY BLADING
- QUANTIFY THE EFFECT OF "TURBULENCE" ON THE PERFORMANCE AND DURABILITY OF TURBOMACHINERY BLADING

PROVIDE AN EXPERIMENTALLY VALIDATED TIME-ACCURATE CALCULATION OF MULTI-STAGE COMPRESSOR BLADE ROW INTERACTIONS

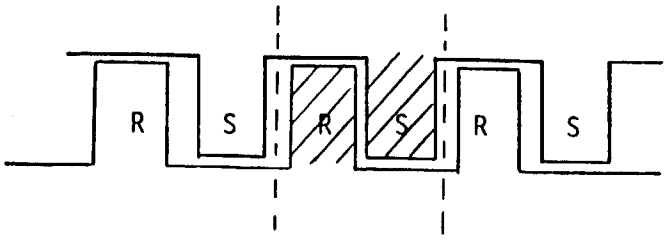
AVAILABLE BLADE ROW INTERACTION CODES

TIME ACCURATE ROTOR/STATOR CODE
ARC, LeRC

LIMITED TO SINGLE STAGE GEOMETRIES FOR CURRENT AND NEXT GENERATION SUPERCOMPUTERS

USED TO PROVIDE CLOSURE MODELS FOR PASSAGE-AVERAGE SIMULATION

PROVIDES TEMPORAL AND SPATIAL FLOW FIELD VARIATIONS

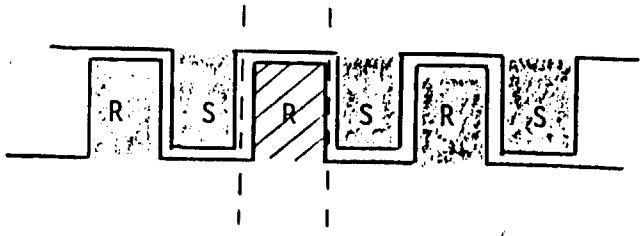


PASSAGE AVERAGE MULTISTAGE CODE
LeRC

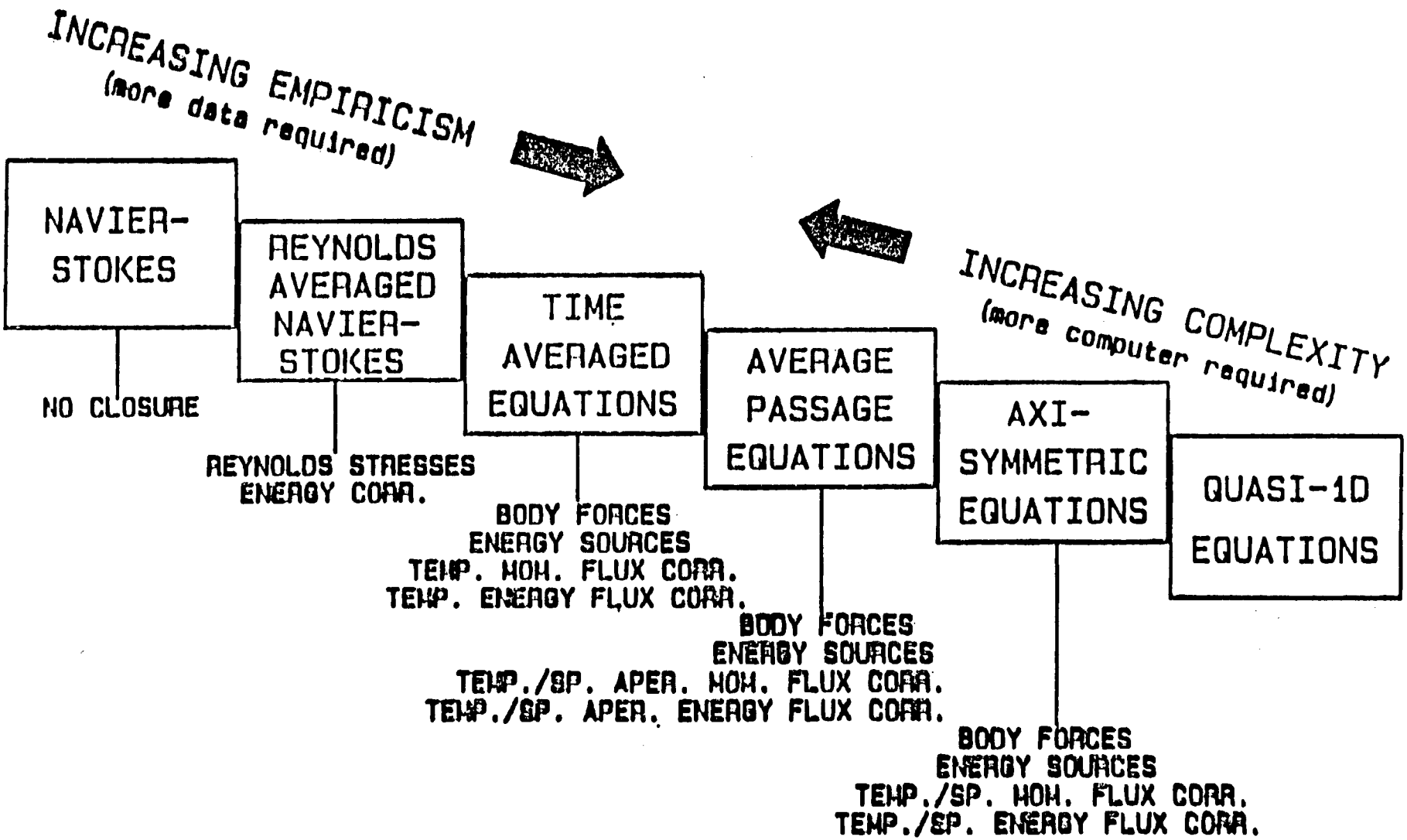
CAPABLE OF SOLVING MULTI-STAGE GEOMETRIES

REQUIRES CLOSURE MODELS FOR TEMPORAL AND SPATIAL MOMENTUM AND ENERGY CORRELATIONS

PROVIDES TIME-AVERAGE FLOW FIELD WITHIN A TYPICAL BLADE PASSAGE



EQUATION HIERARCHY



AVERAGE–PASSAGE ANALYSIS METHOD

- TOTAL VELOCITY IS WRITTEN AS

$$\mathcal{V} = \overline{\overline{\tilde{\tilde{\mathcal{V}}}}} + \overline{\tilde{\tilde{\mathcal{V}}}}' + \tilde{\mathcal{V}}' + \mathcal{V}'$$

TOTAL VELOCITY	SPATIALLY PERIODIC "AVERAGE-PASSAGE" COMPONENT	SPATIALLY APERIODIC COMPONENT	TEMPORALLY PERIODIC COMPONENT	"RANDOM" COMPONENT

- AFTER SUBSTITUTION INTO THE NAVIER–STOKES EQUATIONS AND APPROPRIATE AVERAGING (ANALOGOUS TO REYNOLDS AVERAGING), THE FOLLOWING STRESS TENSOR APPEARS

$$\mathcal{R}_{ij} = \overline{\overline{\tilde{\tilde{\rho}}}\,\overline{\tilde{\tilde{V}}}_i'\,\overline{\tilde{\tilde{V}}}_j'} + \overline{\overline{\tilde{\tilde{\rho}}}\,\tilde{\tilde{V}}_i'\,\tilde{\tilde{V}}_j'} + \overline{\overline{\tilde{\tilde{\rho}}}\,V_i'\,V_j'}$$

- EXPERIMENTAL DATA IS THEN NEEDED TO DEVELOP MODELS FOR ALL THREE COMPONENTS OF THE ABOVE STRESS TENSOR (ANALOGOUS TO TURBULENCE MODELING).

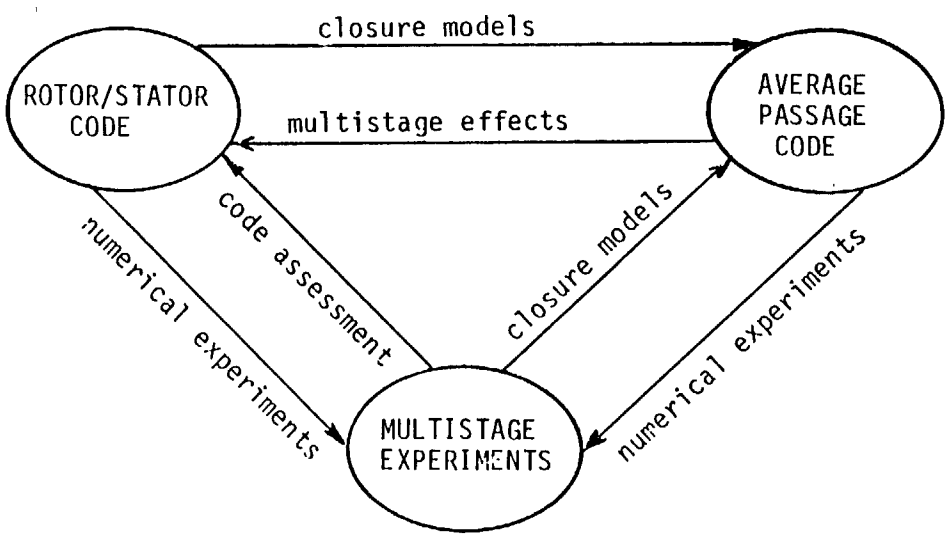
CFD CODE ASSESSMENT

COMPARE TIME-ACCURATE ROTOR/STATOR CODE TO EXPERIMENTAL DATA

COMPARE AVERAGE-PASSAGE MULTI-STAGE CODE TO EXPERIMENTAL DATA

COMPARE AVERAGE PASSAGE CLOSURE MODELS:
- GENERATED BY ROTOR/STATOR CODE
- GENERATED BY EXPERIMENTAL DATA

ASSESS RELATIVE MAGNITUDE OF DETERMINISTIC AND RANDOM UNSTEADINESS



REQUIRED DATA

DATA REQUIRED TO EVALUATE CLOSURE TERMS FOR PASSAGE AVERAGE MULTISTAGE CODE

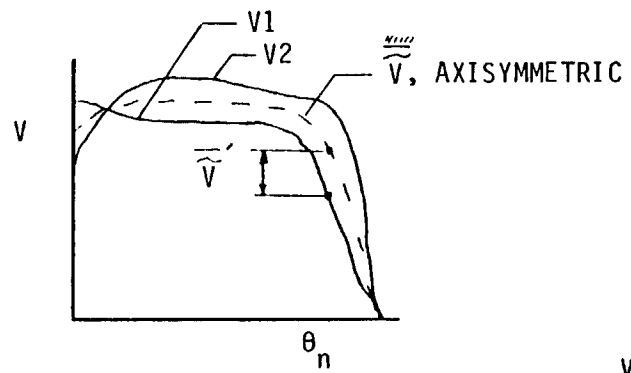
- TIME-DEPENDENT VELOCITY, DENSITY, TEMPERATURE WITHIN THE FLOW FIELD
- TIME-DEPENDENT BLADE SURFACE PRESSURE DISTRIBUTIONS

DATA REQUIRED TO EVALUATE TURBULENT DIFFUSION

- TRACE-GAS SAMPLING RESULTS

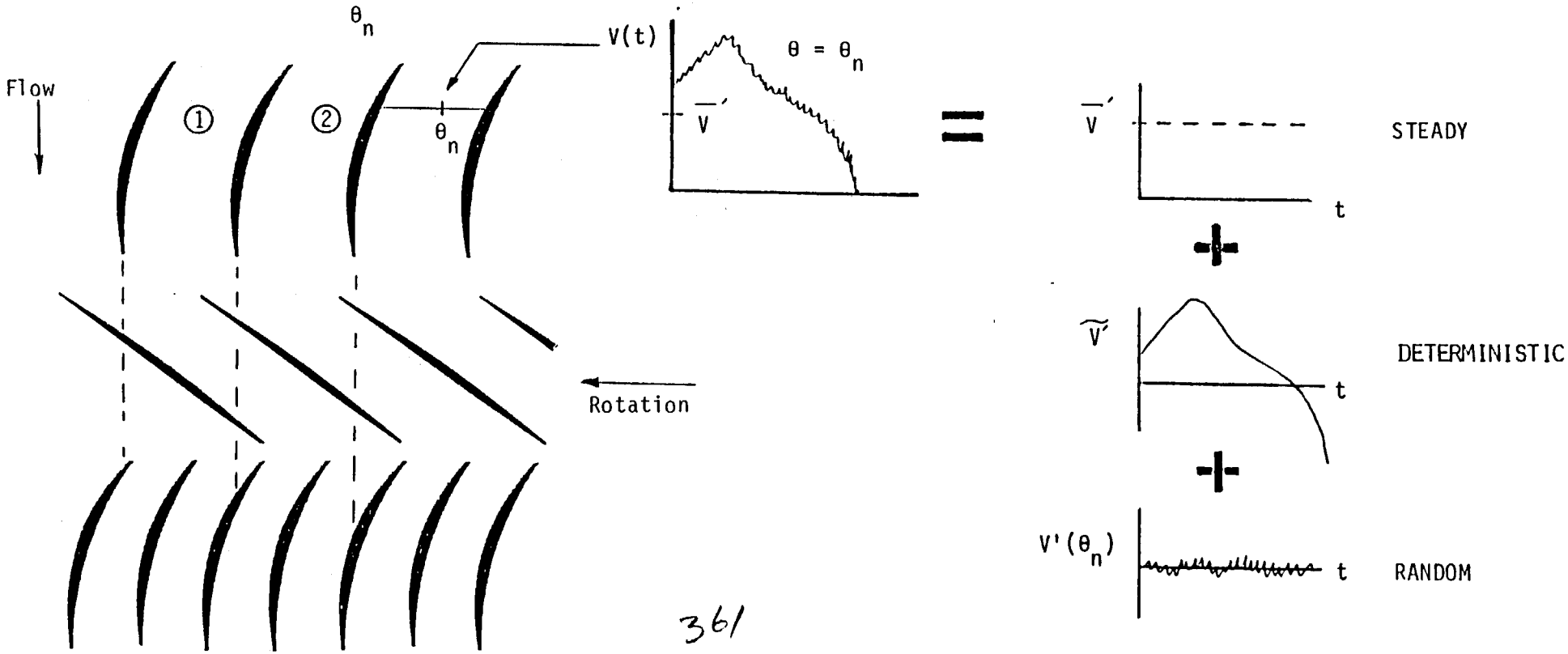
NASA

REQUIRED MEASUREMENTS



NEED TO MEASURE FOLLOWING COMPONENTS OF VELOCITY AND THERMODYNAMIC PROPERTIES THROUGHOUT THE FLOWFIELD:

1) NON-AXISYMMETRIC
2) DETERMINISTIC
3) RANDOM



CURRENT INSTRUMENTATION CAPABILITY

INSTRUMENT SYSTEM	MEASURED QUANTITY	MEASUREMENT REF. FRAME
PITOT STATIC PROBES	STEADY TOTAL, STATIC PRESS	STATIONARY, ROTATING
DYNAMIC PRESS. TRANSDUCERS	UNSTEADY BLADE SURF. PRESS.	STATIONARY, ROTATING
LASER ANEMOMETRY	2D STEADY AND UNSTEADY FLOW	STATIONARY
HOT WIRE ANEMOMETRY	TURBULENT VELOCITY CORRELATIONS	STATIONARY, ROTATING
TRACE-GAS SAMPLING	TURBULENT DIFFUSION RATES	STATIONARY, ROTATING

REQUIRED INSTRUMENTATION CAPABILITY

FIBER OPTIC LASER ANEMOMETRY FOR 3D VELOCITY MEASUREMENTS

OPTICAL DENSITY/TEMPERATURE MEASUREMENT TECHNIQUES FOR ENERGY CORRELATION MEASUREMENTS IN COMPRESSIBLE FLOWS

FACILITY REQUIREMENT

LARGE SIZE, LOW SPEED MULTISTAGE COMPRESSOR FACILITY

ADVANTAGES

- DETAILED MEASUREMENTS WITHIN ENDWALL REGIONS
- ROTATING FRAME INSTRUMENTATION
- REDUCED INSTRUMENTATION BLOCKAGE EFFECTS
- INCOMPRESSIBLE FLOW FOR HOT WIRE TECHNIQUES
- BLADE ROW GEOMETRIES (BLADE COUNT, BLADE PHASE) EASILY CHANGED

HIGH SPEED COMPRESSOR FACILITY

- COMPRESSIBLE FLOW - ENERGY CORRELATIONS IMPORTANT

LOW SPEED AXIAL COMPRESSOR FACILITY

4 1/2 STAGES, 48" DIAMETER, 800 RPM

TIP SPEED = 170 FT/SEC
AXIAL VELOCITY = 80 FT/SEC

FEATURES:

VARIABLE BLADE COUNT IN EACH ROW

VARIABLE BLADE PHASE FORM ROW-TO-ROW (ROTORS AND STATORS)

200 - CHANNEL SLIP-RING FOR ROTATING FRAME:

HOT WIRE
STEADY AND DYNAMIC PRESSURE
THERMOCOUPLE

7-CHANNEL PNEUMATIC SLIP-RING FOR ROTATING FRAME GAS SAMPLING TECHNIQUE

FACILITIES / SCHEDULE

1986 HIGH SPEED SINGLE STAGE	1990 LOW SPEED MULTISTAGE	1992 HIGH SPEED MULTISTAGE
COMPRESSIBLE FLOW	INCOMPRESSIBLE FLOW	COMPRESSIBLE FLOW
"FIXED GEOMETRY"	"VARIABLE GEOMETRY"	"FIXED GEOMETRY"
SINGLE-COMPONENT MOMENTUM CORRELATIONS (2-COMPONENT IN 1989)	3D MOMENTUM AND CORRELATIONS	3D MOMENTUM AND ENERGY CORRELATIONS
NO ENERGY CORRELATION MEASUREMENTS		

PROGRAM SCHEDULE

HIGH SPEED SINGLE STAGE EXPERIMENTS

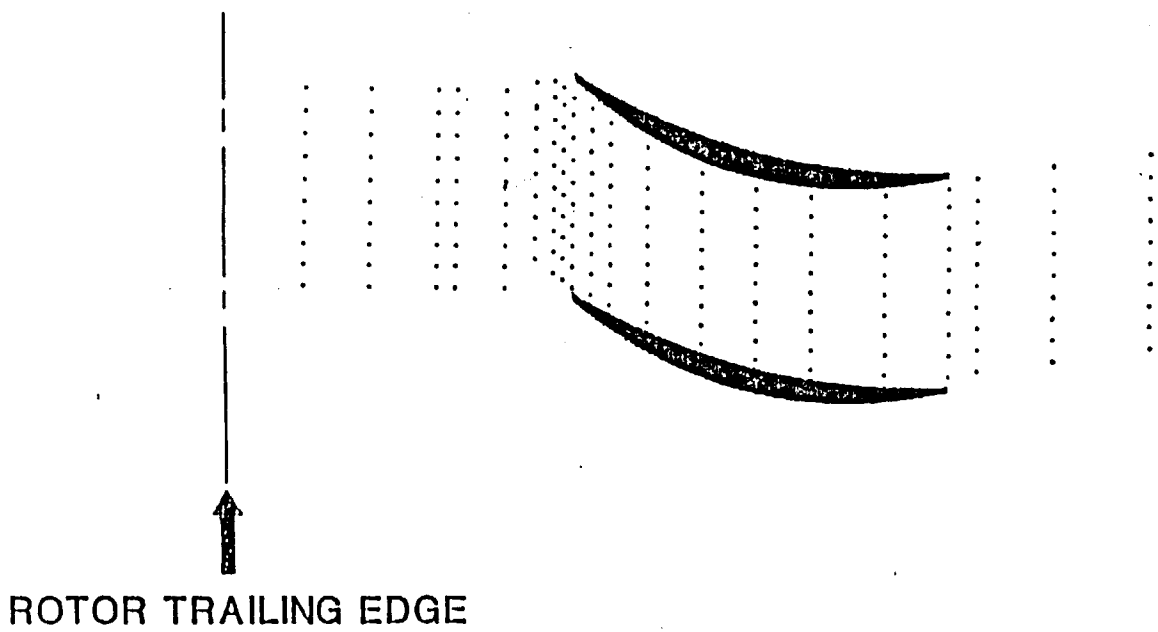
1D DETERMINISTIC AND UNRESOLVED MOMENTUM CORRELATIONS MEASURED IN LOOSELY-COUPLED FAN STAGE	1986
2D MOMENTUM CORRLELATIONS TO BE MEASURED IN A CLOSELY-COUPLED LOW-ASPECT RATIO HIGHLY LOADED COMPRESSOR STAGE	1989

LOW SPEED MULTISTAGE FACILITY

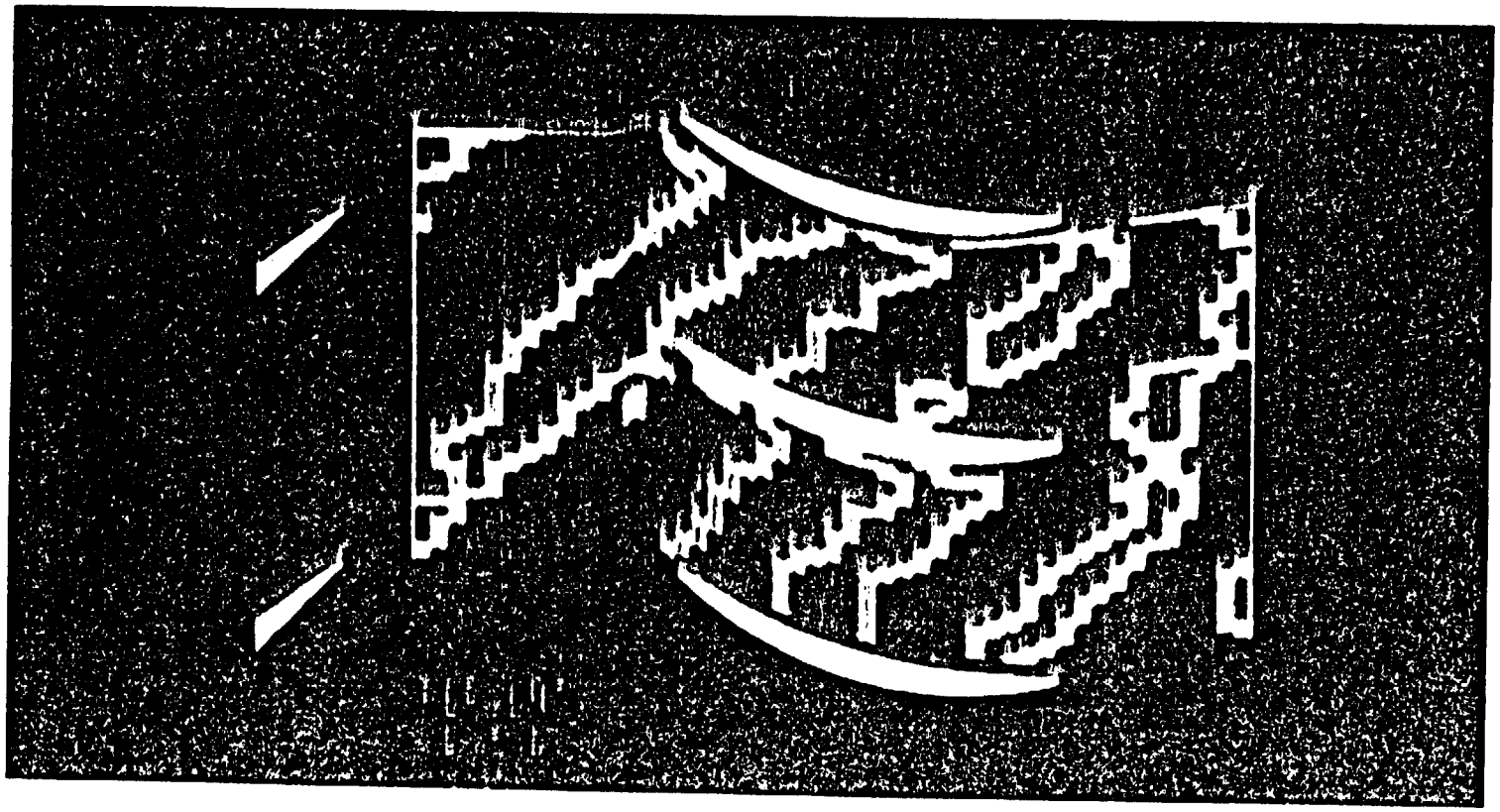
CONCEPTUAL DESIGN STUDY UNDERWAY	1987
MECHANICAL DESIGN COMPLETE	1988
INITIAL OPERATIONAL CAPABILITY	MID-1990

LOOSELY COUPLED FAN STAGE
LASER ANEMOMETER CIRCUMFERENTIAL/AXIAL SURVEY LOCATIONS

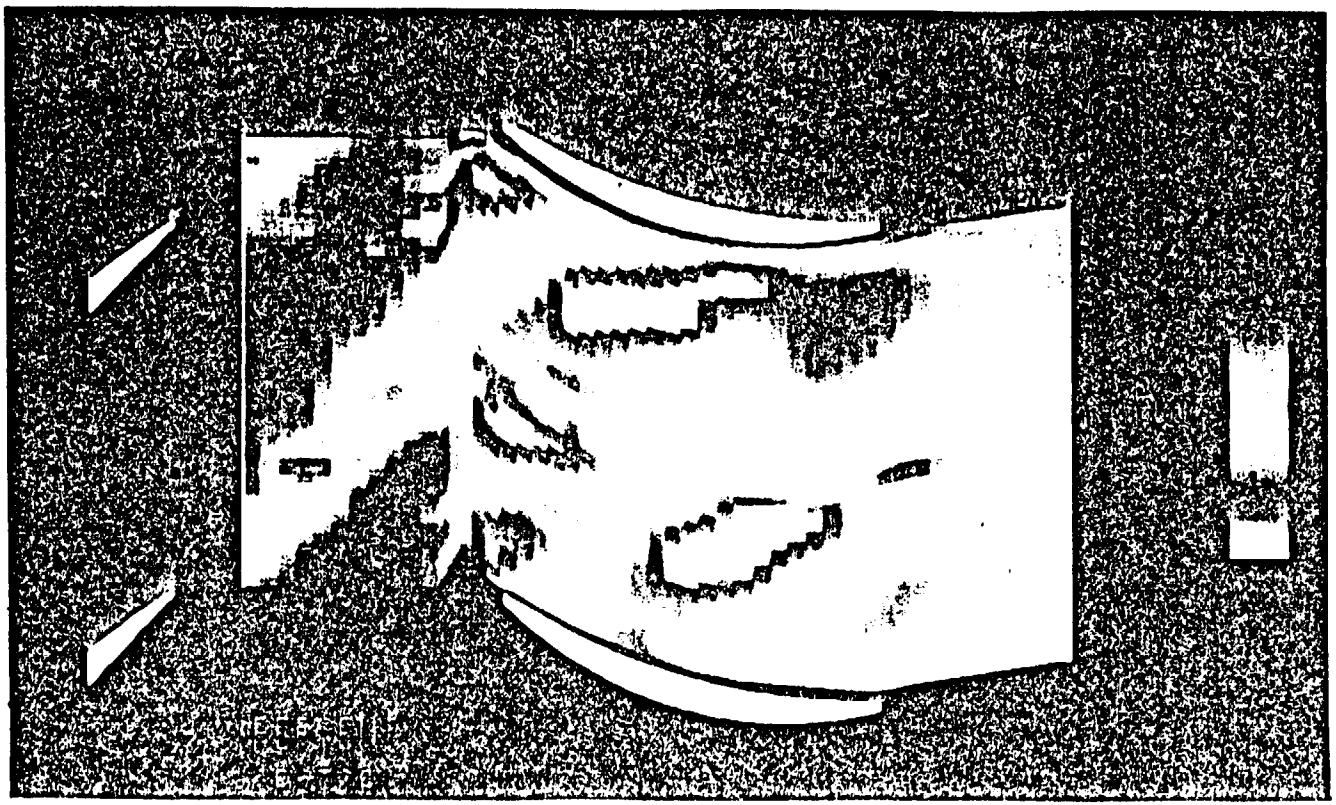
50% SPAN



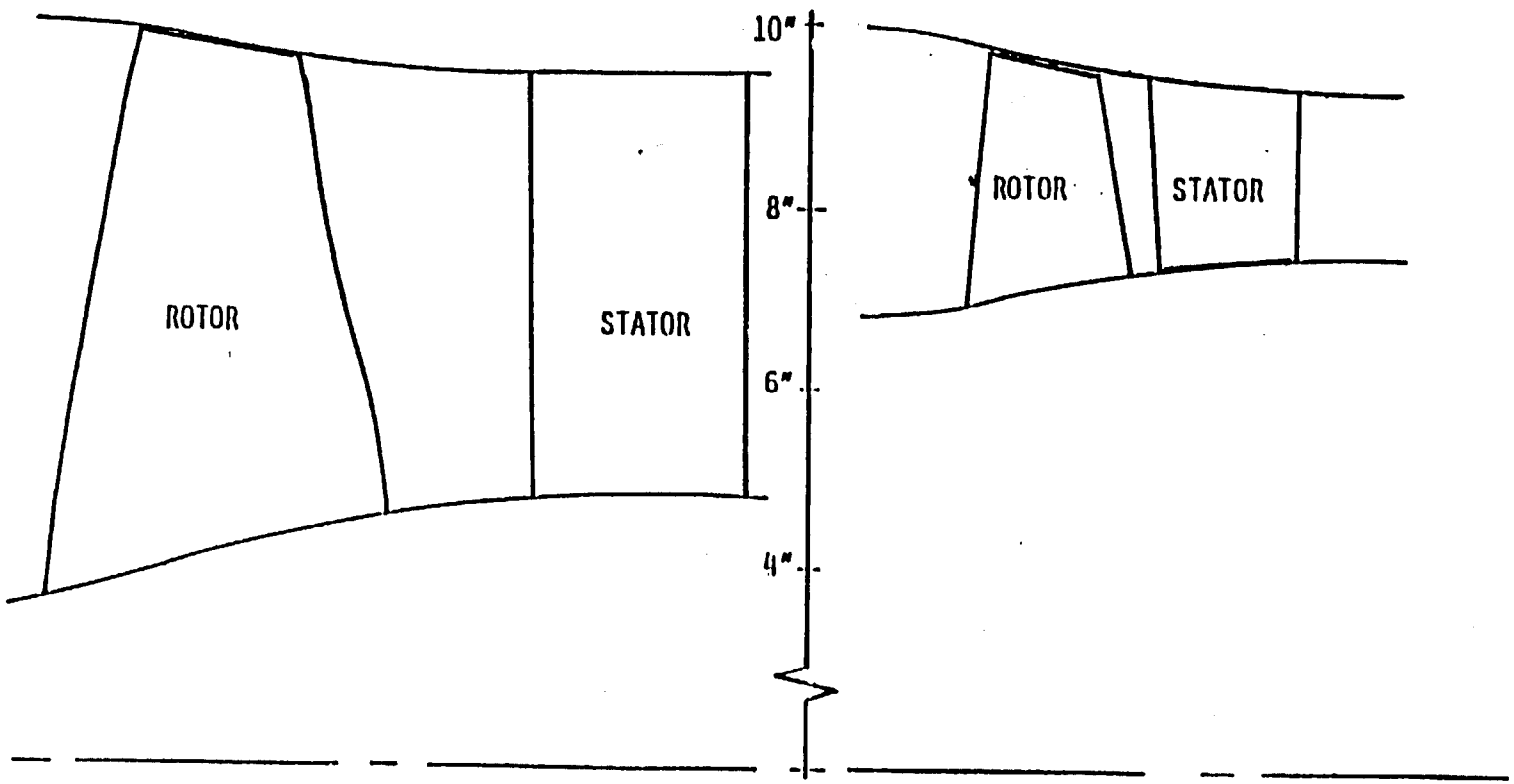
SINGLE STAGE
BLADE ROW INTERACTION RESEARCH
ROTOR WAKE FLUID - FAN STAGE



SINGLE STAGE
BLADE ROW INTERACTION RESEARCH
UNRESOLVED UNSTEADINESS - FAN STAGE



SINGLE STAGE
BLADE ROW INTERACTION RESEARCH



1986
LOOSELY-COUPLED
FAN STAGE
1D MOMENTUM CORRELATIONS

1989
CLOSELY-COUPLED
CORE COMPRESSOR STAGE
2D MOMENTUM CORRELATIONS

PROGRAM STATUS

	1986	1987	1988	1989	1990	1991
HIGH SPEED SINGLE STAGE EXPERIMENTS						
LOOSELY-COUPLED FAN STAGE	▲					
CLOSE-COUPLED CORE COMPRESSOR STAGE				▲		
LOW SPEED MULTISTAGE FACILITY						
CONCEPTUAL DESIGN		▲				
DETAILED MECHANICAL DESIGN			▲			
FABRICATION				▲		
INITIAL OPERATIONAL CAPABILITY					▲	

3D UNSTEADY FLOWS IN MULTISTAGE COMPRESSORS

SUMMARY

UTILIZING BOTH TIME-ACCURATE AND PASSAGE-AVERAGE CODES

CLOSE COUPLING BETWEEN NUMERICAL AND EXPERIMENTAL EFFORTS

INITIAL EXPERIMENTAL RESULTS FROM HIGH-SPEED, SINGLE STAGES

LARGE, LOW-SPEED FACILITY REQUIRED FOR DETAILED MODELING, VALIDATION

INSTRUMENTATION ADVANCES REQUIRED FOR SCALAR MEASUREMENTS IN COMPRESSIBLE FLOWS

Anderson

TITLE: CONFINED SEPARATED-SWIRLING FLOWS IN DIFFUSING DUCTS

OBJECTIVE: ESTABLISH A DETAILED EXPERIMENTAL DATA BASE FOR EVALUATION OF NAVIER-STOKES CODES FOR CONFINED SEPARATED FLOWS IN DIFFUSING S-DUCTS

COMPUTATIONAL THRUSTS:

(1) EXTENSION AND VALIDATION OF LEWIS PNS SOLVER PEPSIG INTO THE SEPARATED FLOW REGIME USING "FLARE" TYPE APPROXIMATIONS

(2) EVALUATION AND EXTENSIONS OF STATE-OF-THE-ART TURBULENCE MODELS FOR CONFINED SEPARATED FLOW WITH AND WITHOUT SWIRL

(3) EVALUATION AND VALIDATION OF LEWIS TIME MARCHING 3D NAVIER-STOKES CODE PROTEUS INTO CONFINED SEPARATED FLOW REGIME

APPROACH: A JOINT ANALYSIS/EXPERIMENTAL PROGRAM WILL BE INITIATED IN WHICH THE EXPERIMENTAL MEASUREMENTS WILL BE PERFORMED AT A UNIVERSITY IN CONJUNCTION WITH AN INHOUSE COMPUTATIONAL EFFORT

N92-70937

MODELS: A CIRCULAR ARC ($R/r \sim 6$) ROUND DIFFUSER OF AREA RATIO 2.0 WILL BE ARRANGED IN THE FORM OF TWO CONNECTING 90 DEGREE BENDS SO AS TO ALLOW A 180 DEGREE INPLANE, 90-90 OUT-OF-PLANE AND 90-90 INPLANE DIFFUSING S-DUCT.

TEST CONDITIONS:

FOR EACH OF THE THREE DUCT CONFIGURATIONS, THREE SETS OF SEPARATED FLOW DATA WILL BE OBTAINED: FOR LAMINAR FLOW AT NOMINAL REYNOLDS NUMBER OF 500 AND 1000, AND TURBULENT FLOW AT A REYNOLDS NUMBER OF 45,000.

PRE-TEST ANALYSIS:

A PRE-TEST ANALYSIS HAS BEEN PERFORMED TO ESTABLISH THE FLOW SEPARATION TOPOLOGIES AND HOW THEY ARE AFFECTED BY COMBINATIONS OF REYNOLDS NUMBER, BOUNDARY LAYER THICKNESS AND SWIRL.

FACILITY & INSTRUMENTATION:

EXPERIMENTS WILL BE CARRIED OUT WITH THE USE OF A COMBINATION OF LASER-VELOCIMETRY, HOT WIRE ANEMOMETRY, PRESSURE TUBES AND FLOW VISUALIZATION. SURVEY PLANES LOCATIONS TO BE ESTABLISHED FROM ANALYSIS OF THE COMPUTATIONAL RESULTS.

3D TIME AVERAGED NAVIER STOKES (PROTEUS) ANALYSIS
CODE CHARACTERISTICS

- 3D ARBITRARY NONORTHOGONAL GEOMETRY
- IMPLICIT (LBI) ALGORITHM
  - FIRST ORDER IN TIME
  - SECOND ORDER IN SPACE
  - VARIABLE SPATIAL DIFFERENCING (BACKWARD - CENTRAL - FORWARD)
- FALL SHOCK CAPTURING ALGORITHM
  - SYMMETRIC TVD SCHEME
  - JAMESON'S ARTIFICIAL VISCOSITY
- PERIODIC IMPLICIT BOUNDARY CONDITIONS
- EQUILIBRIUM AIR CHEMISTRY MODULE
- COMBUSTION CHEMISTRY MODULE

3D PARABOLIZED NAVIER STOKES (PEPSIS) ANALYSIS
CODE CHARACTERISTICS

- 3D GENERAL GEOMETRY CAPABILITY
- IMPLICIT (LBI) ALGORITHM
  - STREAM FUNCTION VORTICITY FORMULATION FOR SECONDARY FLOW
  - UPWIND DIFFERENCING IN STREAMWISE DIRECTION
  - CENTRAL DIFFERENCING IN TRANSVERSE PLANE
- FLARE APPROXIMATION FOR SEPARATED FLOW
- ALGEBRAIC TURBULENCE MODEL
- HEAT TRANSFER CAPABILITY

3D PARABOLIZED NAVIER STOKES (PEPSIS) ANALYSIS COMPUTATIONAL ISSUES

- FLARE APPROXIMATIONS
- SINGLE PASS CALCULATIONS
- MULTI PASS CALCULATIONS

TURBULENT MODEL ISSUES

- EFFECTIVE VISCOUSITY MODELS
  - INFLUENCE OF SEPARATIONS
  - EFFECT OF SWIRL

- STRESS-BASED TURBULENCE MODELS
  - EFFECT OF STRESS DRIVEN SECONDARY FLOWS

3D TIME AVERAGED NAVIER STOKES (PROTEUS) ANALYSIS COMPUTATIONAL ISSUES

- TURBULENCE MODELS
- GRID RESOLUTION
- ARTIFICAL VISCOUSITY
- BOUNDARY CONDITIONS

CFD VALIDATION EXPERIMENTS
TEST CONDITIONS

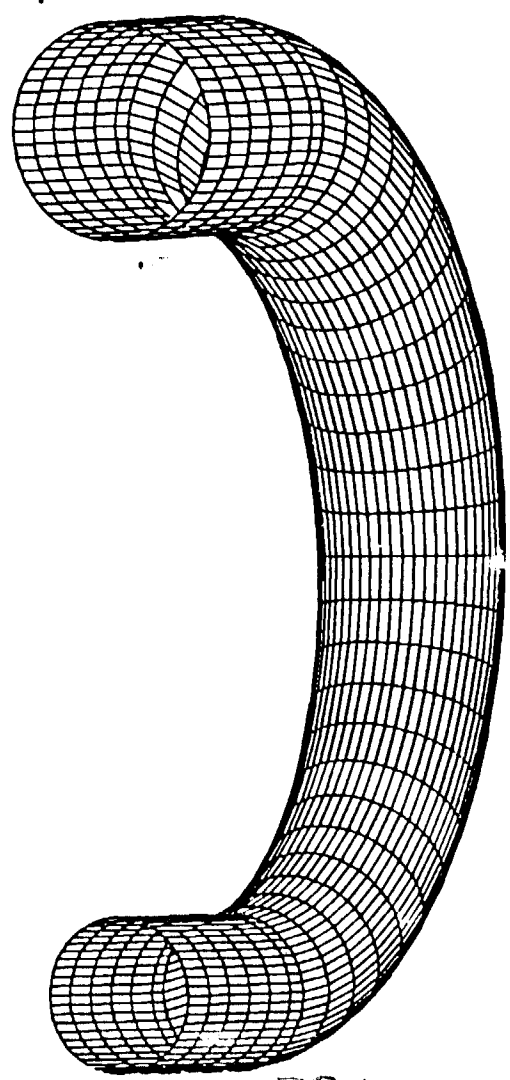
NOMINAL REY. NO.	FLOW	δ/R	SWIRL (DEG.)	CONF. (1) 180/0/0	CONF. (2) 90/90/0	CONF. (3) 90/0/90
500	LAMINAR	0.2	0	CS	CS	CS
			30	CS	CS	SF
			60	AF	CS	CS
		1.0	0	CS	SF	SF
			30	CS	CS	SF
1000	LAMINAR	0.2	0	CS	CS	SF
			30			
			60			
		1.0	0			
			30			
45.000	TURBULENT	0.2	0	CS	CS	SF
			30			
			60			
		1.0	0			
			30			
			60			

AF = ATTACHED FLOW CS = CONFINED SEPARATION SF = SEPARATED FLOW

National Aeronautics and
Space Administration
Lewis Research Center

COMPUTATIONAL METHODS BRANCH

CFD VALIDATION DIFFUSING DUCTS
180 Degree Inplane Geometry, Conf. No. 1



National Aeronautics and
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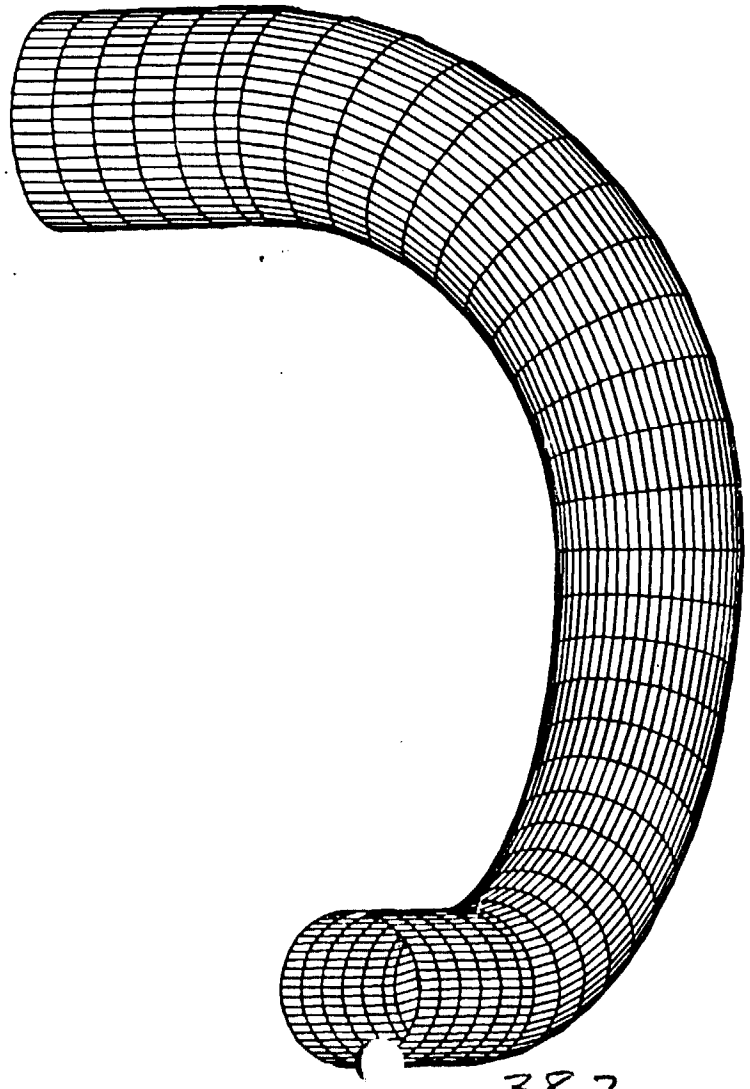
Lewis Research Center

COMPUTATIONAL METHODS BRANCH

NASA

CFD VALIDATION DIFFUSING DUCTS
90/90 Degree Out-of-plane Geometry, Conf. No. 2



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VALD VG200

National Aeronautics and
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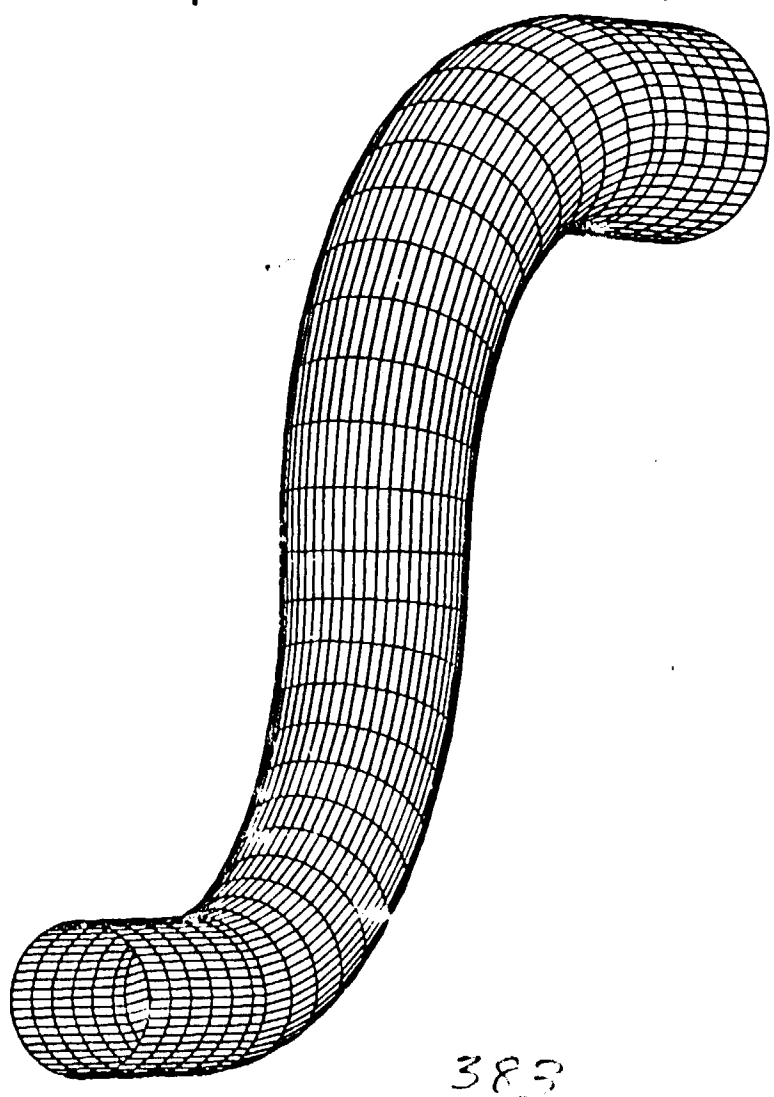
COMPUTATIONAL METHODS BRANCH

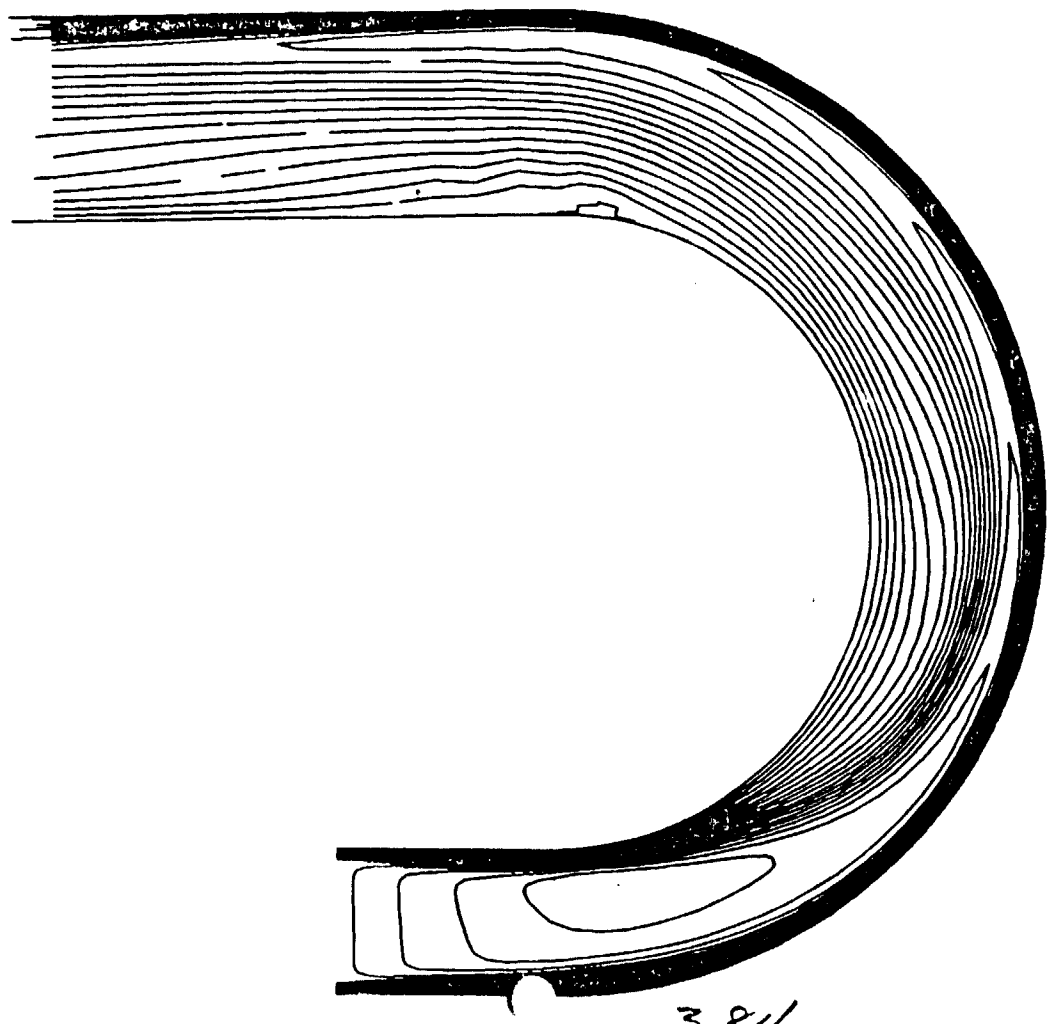
NASA

CFD VALIDATION DIFFUSING DUCTS
90/90 Degree Inplane Geometry, Conf. No. 3



VALD VG300

180 INPLANE DUCT GEOMETRY, CONF. NO. 1
Rey = 500, Laminar Flow, d/R =0.2, Swirl = 0.0
Velocity Contours in Vertical Plane



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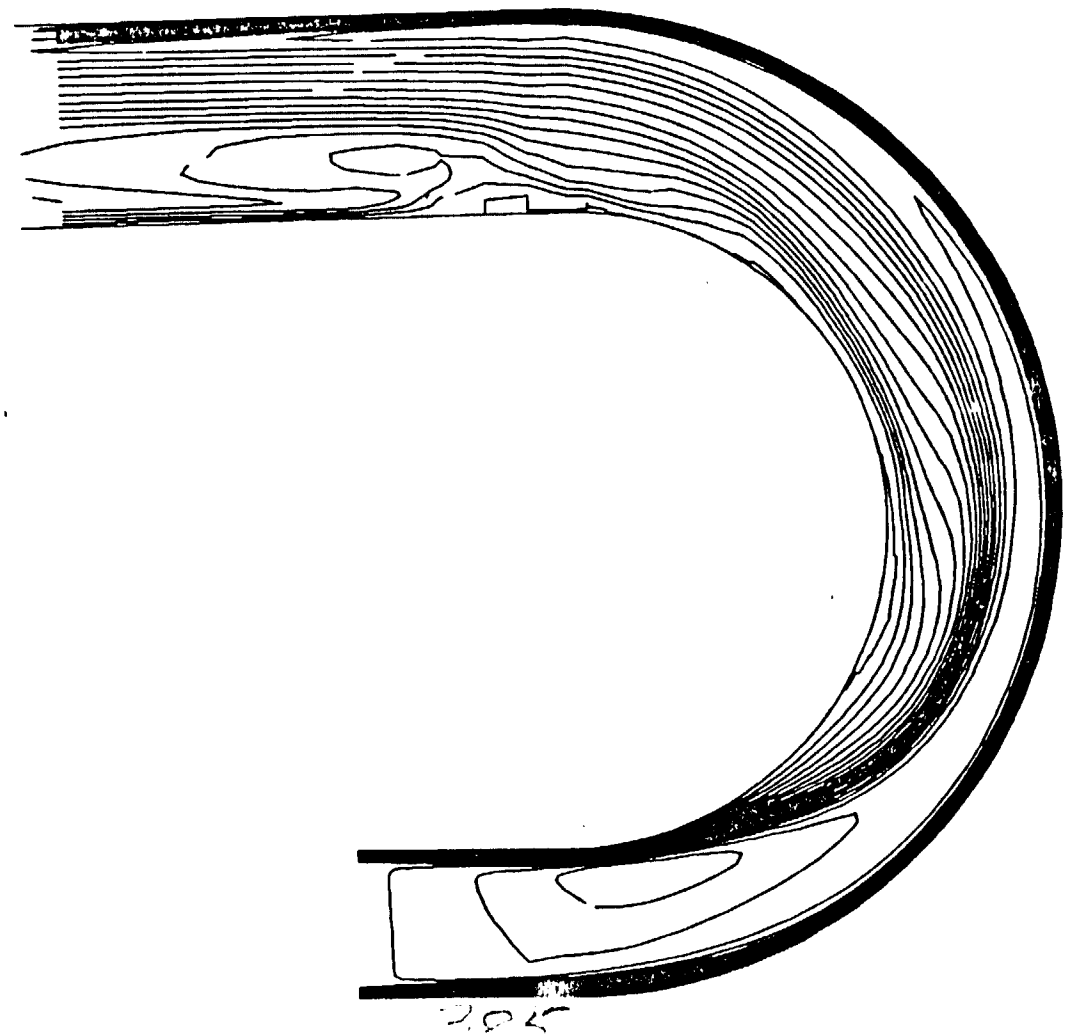
Lewis Research Center

COMPUTATIONAL METHODS BRANCH

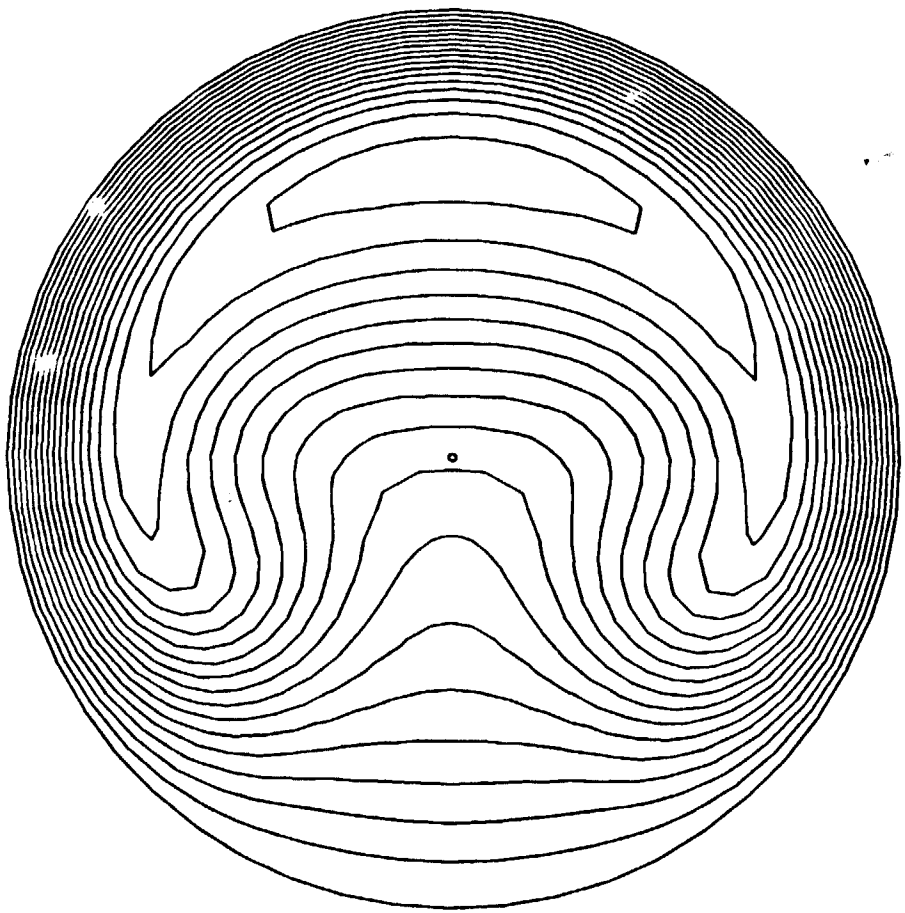
NASA

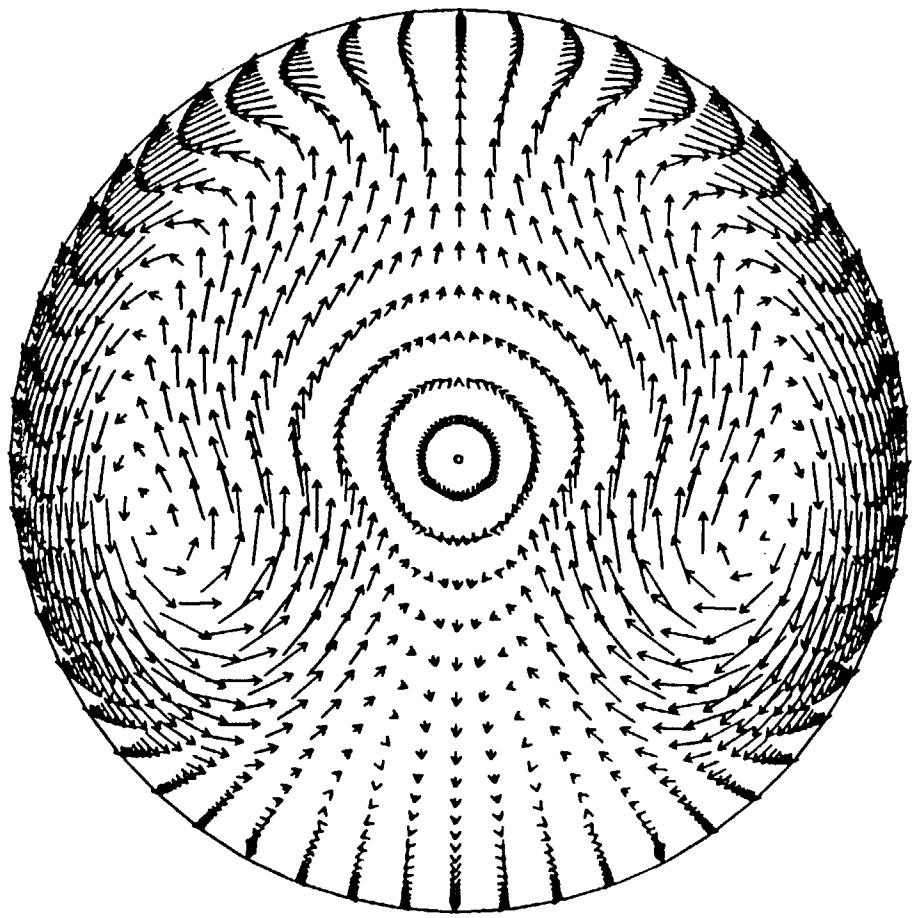
180 INPLANE DUCT GEOMETRY, CONF. NO. 1
Rey = 1000, Laminar Flow, d/R =0.2, Swirl = 0.0
Velocity Contours in Vertical Plane



VALD VG105

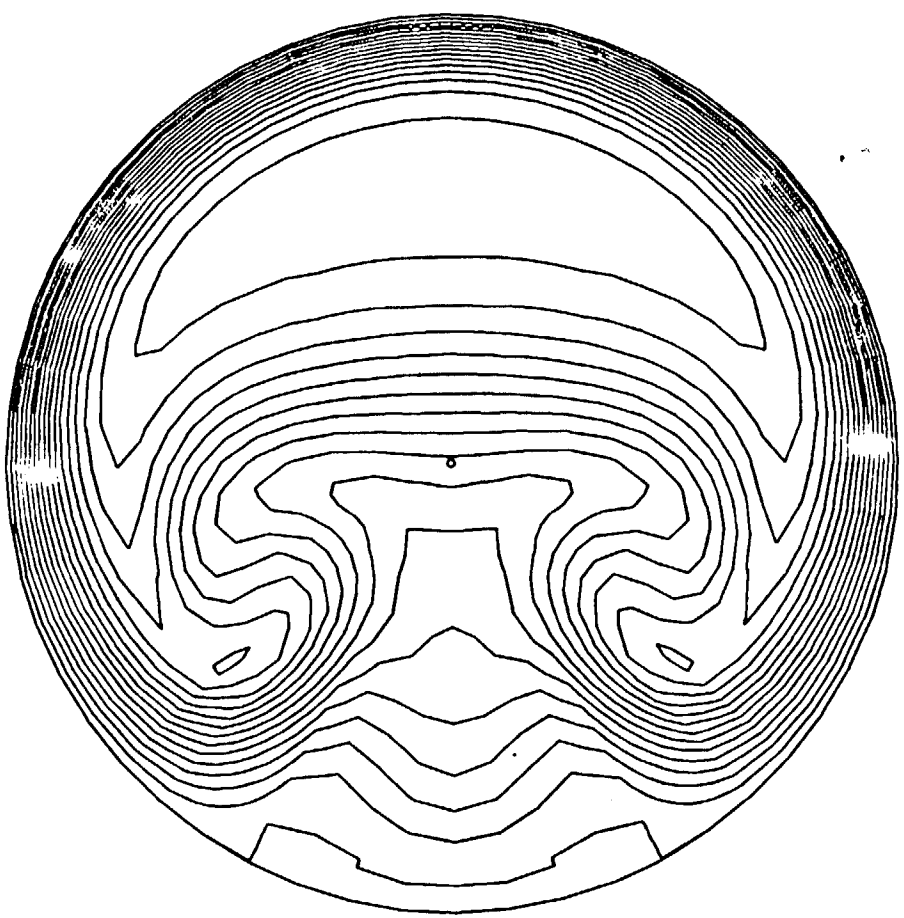
180 INPLANE DUCT GEOMETRY, CONF. NO. 1
Rey = 500, Laminar Flow, d/R =0.2, Swirl = 0.0
Streamwise and Secondary Velocity, Theta = 90.0

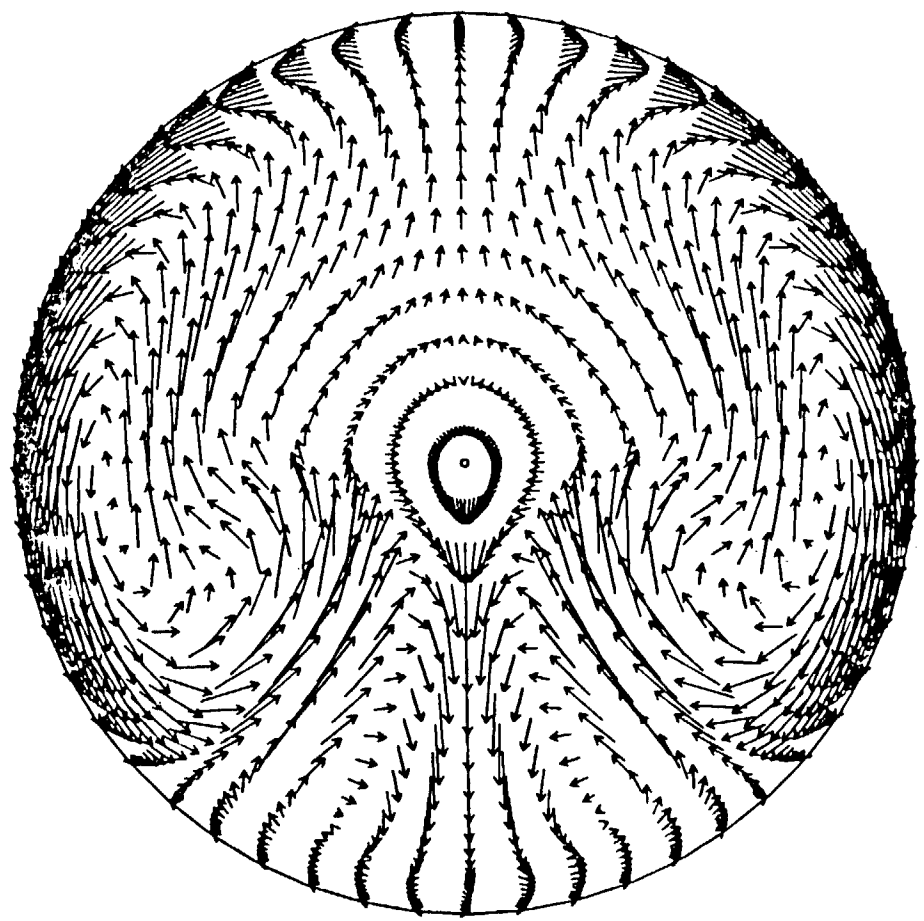




3°6

180 INPLANE DUCT GEOMETRY, CONF. NO. 1
Rey = 1000, Laminar Flow, d/R =0.2, Swirl = 0.0
Streamwise and Secondary Velocity, Theta = 90.0





INSTRUMENTATION

- LASER VELOCIMETER
- HOT WIRE ANEMOMETRY
- STATIC PRESSURE TUBES
- FLOW VISUALIZATION

FUNDING

120K/YEAR FOR THREE YEARS

National Aeronautics and
Space Administration
Lewis Research Center

INTERNAL FLUID MECHANICS DIVISION

NASA

HEAT TRANSFER IN 3D FLOW REGIONS GENERATED BY INTERSECTING SURFACES

Presentation to the
FIRST NASA CFD VALIDATION WORKSHOP
NASA Ames Research Center
July 14–16,1987

by
Robert J. Simoneau
Raymond E. Gaugler

RESEARCHERS

- COMPUTATIONAL
  Rodrick V. Chima, John R. Schwab
- EXPERIMENTAL
  Isaac Lopez,* G. James Van Fossen

* USAARTA

N92-70938

HEAT TRANSFER IN 3D FLOW REGIONS

PROGRAM MOTIVATION

- Critical heat transfer problems exist in 3D flows such as turbine passage endwalls
- 3D secondary flows, functions of
  - Horseshoe vortex
  - Cross–passage pressure gradients
  - Strong flow turning
- 2D computations are inadequate

PROGRAM OBJECTIVE

- Validate code capabilities to model and predict the critical physics associated with heat transfer in highly 3D flows.
  - Turbulent shear stress model
  - Turbulent heat transfer model
  - Wall Thermal boundary conditions

(3)

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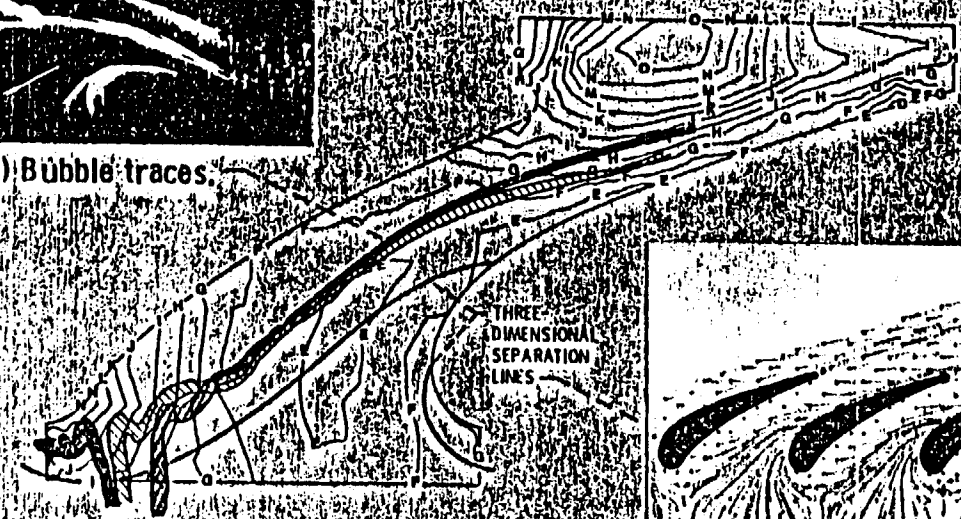
INTERNAL FLUID MECHANICS DIVISION

NASA

FLOW VISUALIZATION TO AID IN INTERPRETATION OF ENDWALL HEAT TRANSFER

(a) Bubble traces.



(c) Stanton number contours. (Increasing D → O).

(b) Ink dots.

Gaugler, Russell

NASA LEWIS 3D VISCOUS CODES

RVC3D

EXPLICIT MULTIGRID THIN-LAYER NAVIER-STOKES CODE

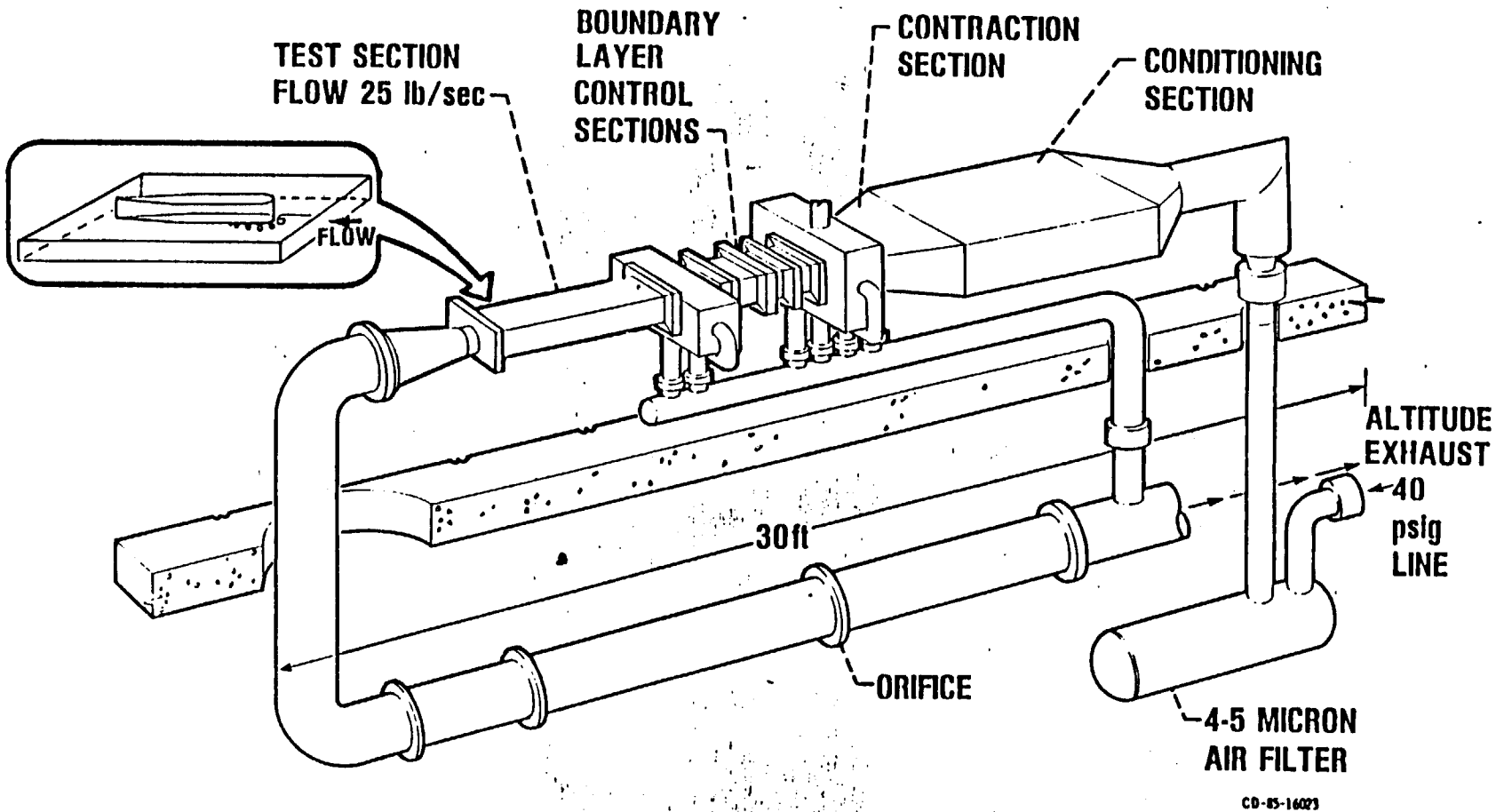
- State-of-the-art transonic solver
- General, non-orthogonal coordinate system
- Thin-layer Navier-Stokes, with energy equation
- Explicit Runge-Kutta time stepping
- Multi-grid convergence acceleration
- Baldwin-Lomax turbulence model

PROTEUS

IMPLICIT 3D FULL NAVIER-STOKES TEST-BED SOLVER

- Readily modified, well documented, general solver
- General, non-orthogonal coordinate system
- Full Navier-Stokes, with energy equation
- Linearized block implicit (LBI) solver
- Convergence acceleration by time-step cycling and matrix preconditioning
- Cebeci-Smith turbulence model in initial configuration

3-D COMPRESSIBLE FLOW TUNNEL



RVC3D LAMINAR HORSESHOE VORTEX CALCULATION
3-D COMPRESSIBLE FLOW TUNNEL

PARAMETERS

Plate Thickness = 1.0 inch

Inlet Boundary Layer Thickness = 0.15 inch

Inlet Mach Number = 0.3

Plate Thickness Reynolds Number = 2500.

Grid = 65 X 29 X 21

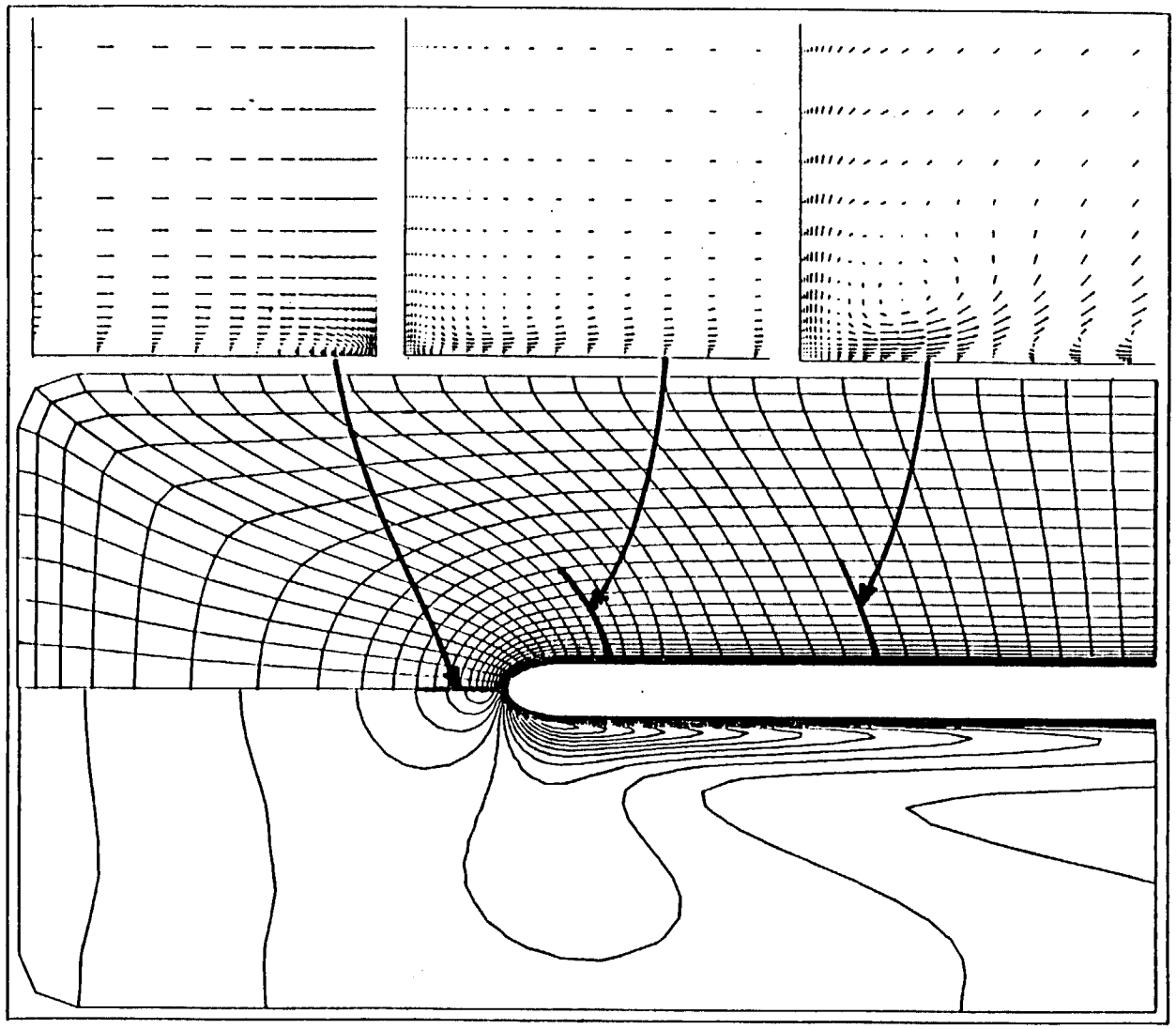
Initial Spacing = 0.01 inch

RVC3D LAMINAR HORSESHOE VORTEX CALCULATION
3-D COMPRESSIBLE FLOW TUNNEL

SECONDARY VELOCITY VECTORS

COMPUTATIONAL GRID (65 x 29 x 21)

MACH NUMBER CONTOURS (6 Grid Points Off Endwall)

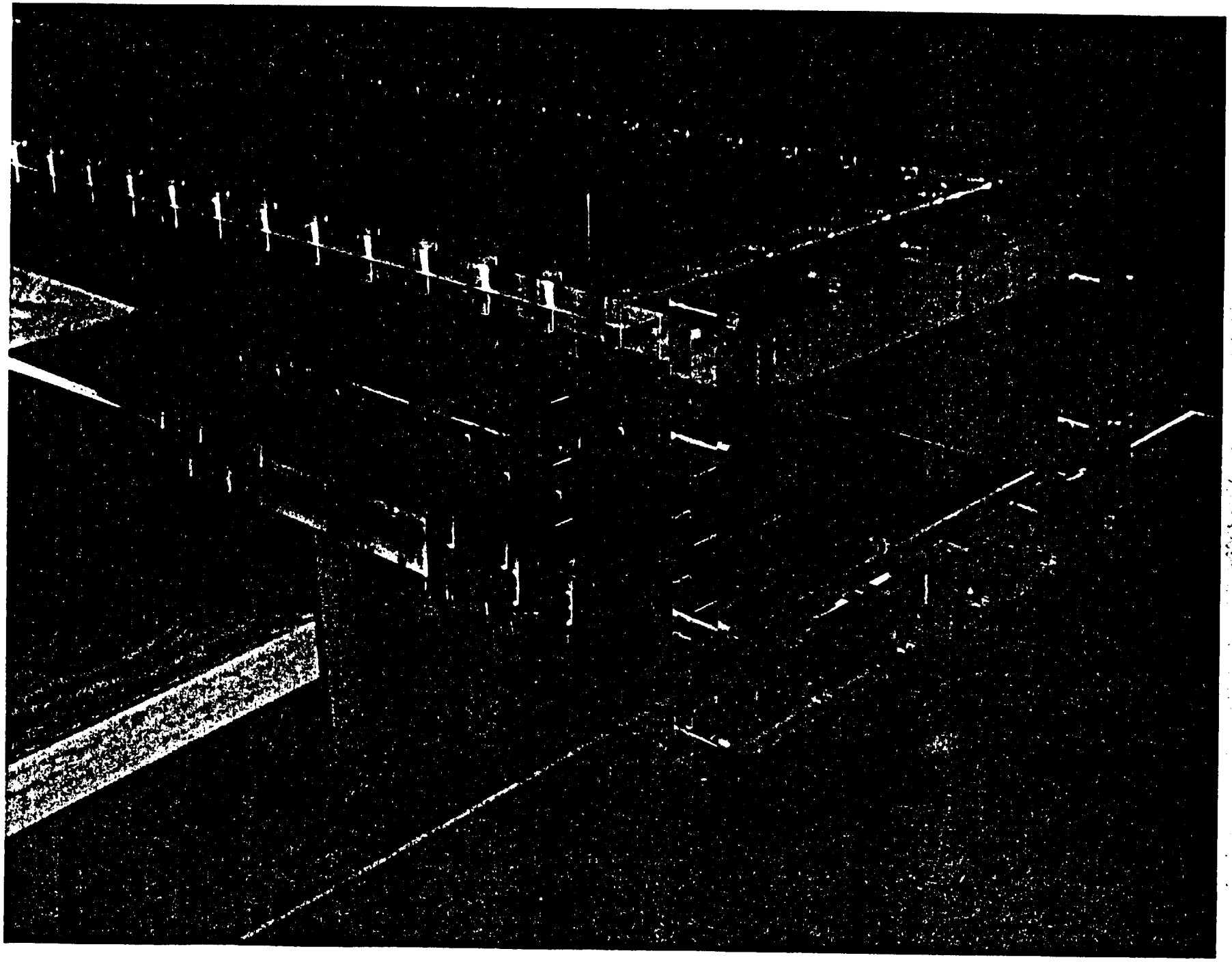


3D HEAT TRANSFER CODE VALIDATION EXPERIMENT

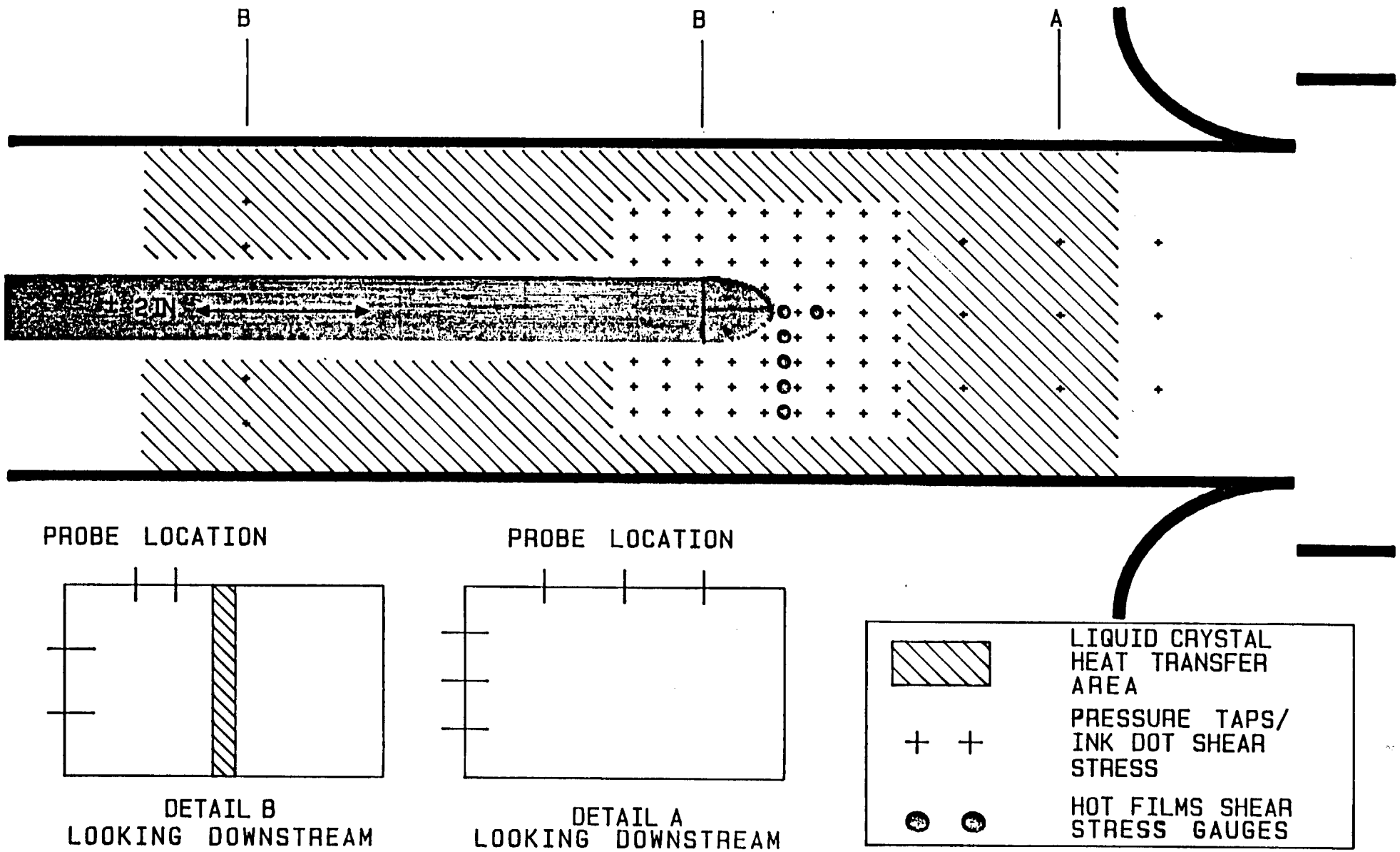
3D COMPRESSIBLE FLOW TUNNEL

- Isolate horseshoe vortex effects from cross passage pressure gradient effects
- Extensive instrumentation, including high resolution liquid crystal heat transfer measurements
- Design and instrumentation layout the result of interaction with code developers
- Range of variables
  - Reynolds Number, $8.5 - 37 \times 10^4$
  - Mach Number, 0.15 – 0.6
  - Inlet Boundary Layer, 0.77 – 1.35 inches

NASA
C-87-5292



3-D COMPRESSIBLE FLOW TUNNEL
TEST SECTION - INSTRUMENTATION



MEASUREMENTS IN 3D COMPRESSIBLE FLOW TUNNEL

PHASE I – Establish Facility, Preliminary Data

- Pressures – surface and field
- Flow angles
- Turbulence intensity
- Surface flow visualization
- Surface shear stress

PHASE II – Detailed Validation of Critical Physics Modeled by Code

A. Heat Transfer.

- Local, high resolution
  - Liquid crystals
  - Constant flux surface

B. Flow Field.

- Laser light sheet visualization
- Two-color LDA
- Hot wire anemometry
  - Turbulence
  - Velocity correlations

National Aeronautics and

Space Administration

Lewis Research Center

INTERNAL FLUID MECHANICS DIVISION

PLANAR COMPRESSIBLE REACTING SHEAR LAYER

Presented at

NASA CFD Validation workshop

July 14–16, 1987

C. Marek

— Principal Investigator

E. Mularz

— Chief, Aerothermochemistry

N92-70939

ATC28

HEAT TRANSFER IN 3D FLOW REGIONS GENERATED BY INTERSECTING SURFACES

RESOURCES / STAFFING / PACE

FY	87	88	89	90	91	
CODE DEVELOPMENT	75	150	150	150	150	K$ NET R & D
	2	2	2	2	2	MY CS
		1 2		3	4	

1. RVC3D CODE WITH HEAT TRANSFER OPERATIONAL
2. PROTEUS CODE WITH HEAT TRANSFER OPERATIONAL
3. CODES ASSESSED AGAINST PRELIMINARY DATA
4. CODES VALIDATED AGAINST INTERSECTING SURFACE DATA

VALIDATION EXPERIMENT	50	150	150	100	50	K$ NET R & D
	4	2	3	2	2	MY CS
		1 2		3	4	

1. PHASE I – PRELIMINARY DATA COMPLETE
2. PHASE IIA – HIGH RESOLUTION HEAT TRANSFER DATA COMPLETE
3. PHASE IIB – FIRST FULL FLOW FIELD MEASUREMENT DATA ACQUIRED
4. PHASE IIB – FULL FLOW FIELD MEASUREMENT DATA COMPLETE

CHEMICAL REACTING FLOWS

Long term goal: *Accurate predictive code with coupled fluid mechanics and chemistry for future aerospace propulsion*

- Enabling technology for advanced capability aircraft
- Progress in last 15 years good, but better understanding required
- Development of CFD codes for internal, turbulent, compressible, reacting flow
- Experimental investigations:
  - Understand physics and chemistry of reacting flow
  - Datasets for code validation and assessment

PLANAR COMPRESSIBLE REACTING SHEAR LAYER EMPHASIZING PRESSURE WAVE - SHEAR LAYER INTERACTION

OBJECTIVE: OBTAIN TIME-DEPENDENT REACTING HYDROGEN DATA OF VELOCITIES AND CONCENTRATIONS. MEASURE COUPLING BETWEEN SHEAR LAYER MOVEMENTS AND PRESSURE FLUCTUATIONS. USE FLOW VISUALIZATION TO OBSERVE PHYSICS.

APPROACH: THE INTERNAL FLUID MECHANICS DIVISION AT THE LEWIS RESEARCH CENTER WILL COORDINATE THE EXPERTISE IN CFD, ACOUSTICS, AND COMBUSTION TO EXAMINE THE SHEAR LAYER INSTABILITIES CAUSED BY FLUID SHEAR, PRESSURE FLUCTUATIONS AND COMBUSTION IN THE SUBSONIC COMPRESSIBLE FLOW REGION TO MACH 1. ADVANCED LASER DIAGNOSTICS WILL BE USED.

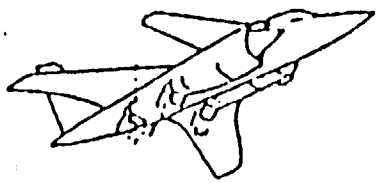
CODE: UNSTEADY STATE TWO-DIMENSIONAL FLOW CODE WITH -

- o PRESSURE OSCILLATION - FLUID INTERACTIONS
- o COMBUSTION - PRESSURE INTERACTIONS
- o FINITE KINETICS.

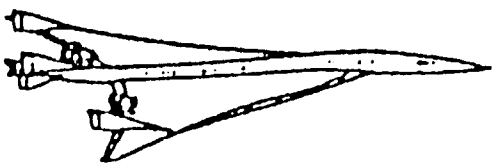
FACILITIES: A COMBUSTOR TEST CELL IS BEING MADE AVAILABLE FOR INSTALLATION OF THE RIG IN NOVEMBER 1987. INITIAL TESTS WILL BE AIR-AIR-TESTS, FOLLOWED BY AIR-HEATED AIR-TESTS WITH COMBUSTION TEST BEGINNING IN MARCH OF 1988.

APPLICATION OF CODE

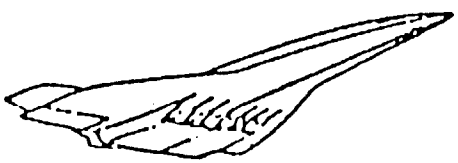
Supersonic STOVL/SUMA



High Mach Recon/Transport



Hypersonics



Propulsion systems dominated by turbulence / chemistry interactions

↓

Time–dependent unsteady chemical reacting flow

↓

Code: MRVC2D

UNSTEADY TWO-DIMENSIONAL COMPRESSIBLE REACTING CODE-MRVC2D

- VERSION OF CHIMA CODE WITH AXIAL DIFFUSION AND KINETICS ADDED
  - EXPLICIT
  - TIME ACCURATE - 4TH ORDER RUNGE KUTTA
  - COMPRESSIBLE
  - ELLIPTIC
- COMPUTE LARGE SCALE ROLLUP DUE TO PRESSURE WAVES
- COMPUTE CHEMICAL REACTION - MIXING INTERACTIONS
- USE VARIABLE PRESSURE BOUNDARY CONDITIONS TO MATCH THE IMPEDENCES OF INCOMING AND OUTGOING FLOWS

CD-87-27653

PLANE MIXING LAYER SELECTED

- Lends itself to modern nonperturbing diagnostics
- Well suited to numerical computations
- Primarily 2–D flow
  - Early experimental results
  - Easier code development and validation
- Convenient starting point for more complex flows of interest
  - flow dynamics
  - 3–D flow effects, geometry
  - supersonic flows

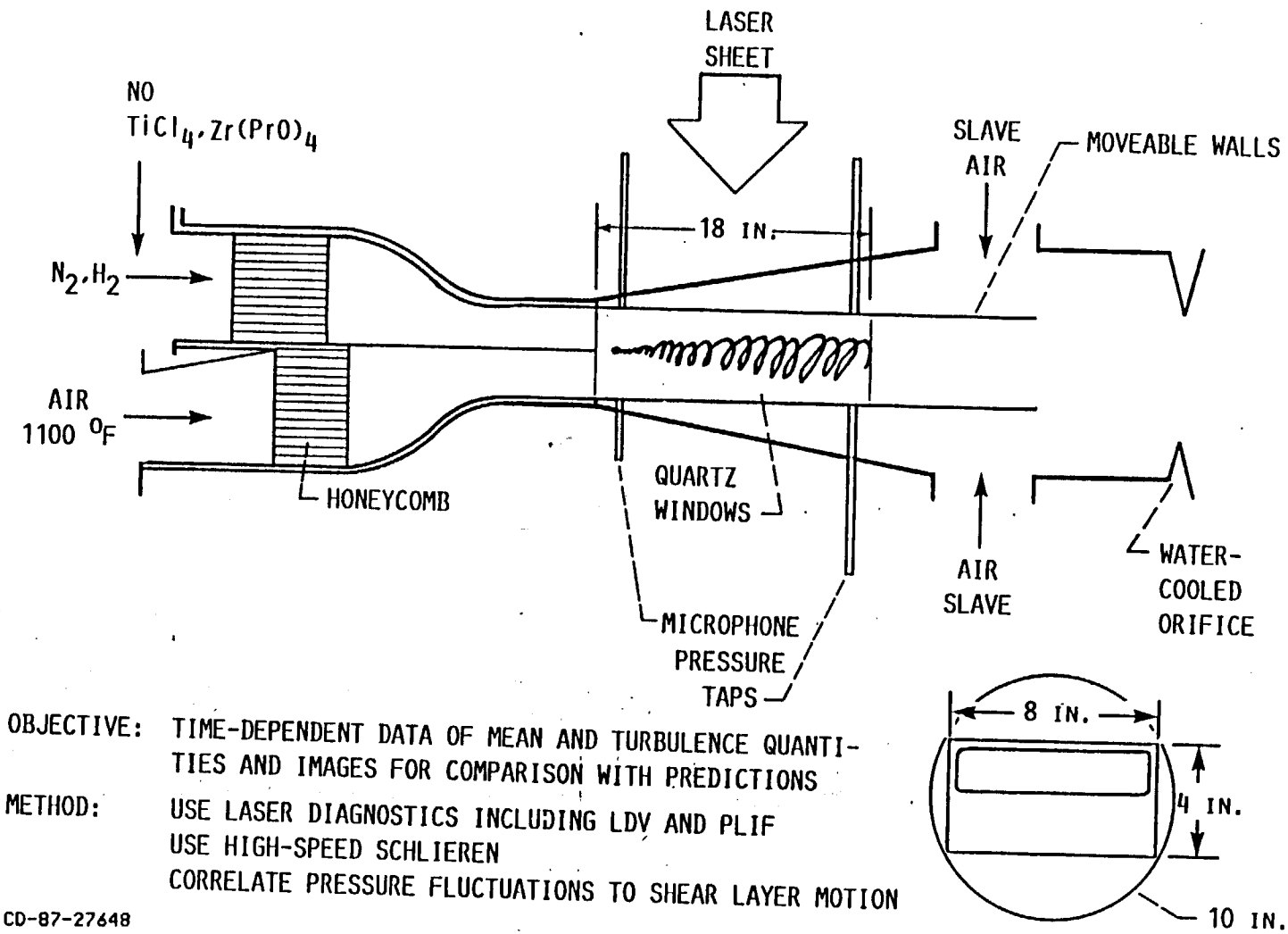
PLANAR COMPRESSIBLE REACTING SHEAR LAYER

CRITICAL NEEDS IN SHEAR LAYER PHYSICS

1. OBTAIN CORRELATION OF PRESSURE OSCILLATIONS TO LARGE EDDY FORMATION.
2. OBTAIN DATA AT HIGH HEAT RELEASE - CORRELATE COMBUSTION RATES TO EDDY GROWTH RATES AND PRESSURE CHANGES.
3. MAKE MEASUREMENTS IN HIGH SPEED - COMPRESSIBLE FLOWS.
4. OBTAIN HIGH PRESSURE DATA BY USING A DOWNSTREAM NOZZLE.
5. LOOK AT EFFECTS OF OSCILLATING PRESSURE FIELD ON SHEAR LAYERS.

CD-87-27651

PLANAR COMPRESSIBLE REACTING SHEAR LAYER



OBJECTIVE: TIME-DEPENDENT DATA OF MEAN AND TURBULENCE QUANTITIES AND IMAGES FOR COMPARISON WITH PREDICTIONS

METHOD: USE LASER DIAGNOSTICS INCLUDING LDV AND PLIF
USE HIGH-SPEED SCHLIEREN
CORRELATE PRESSURE FLUCTUATIONS TO SHEAR LAYER MOTION

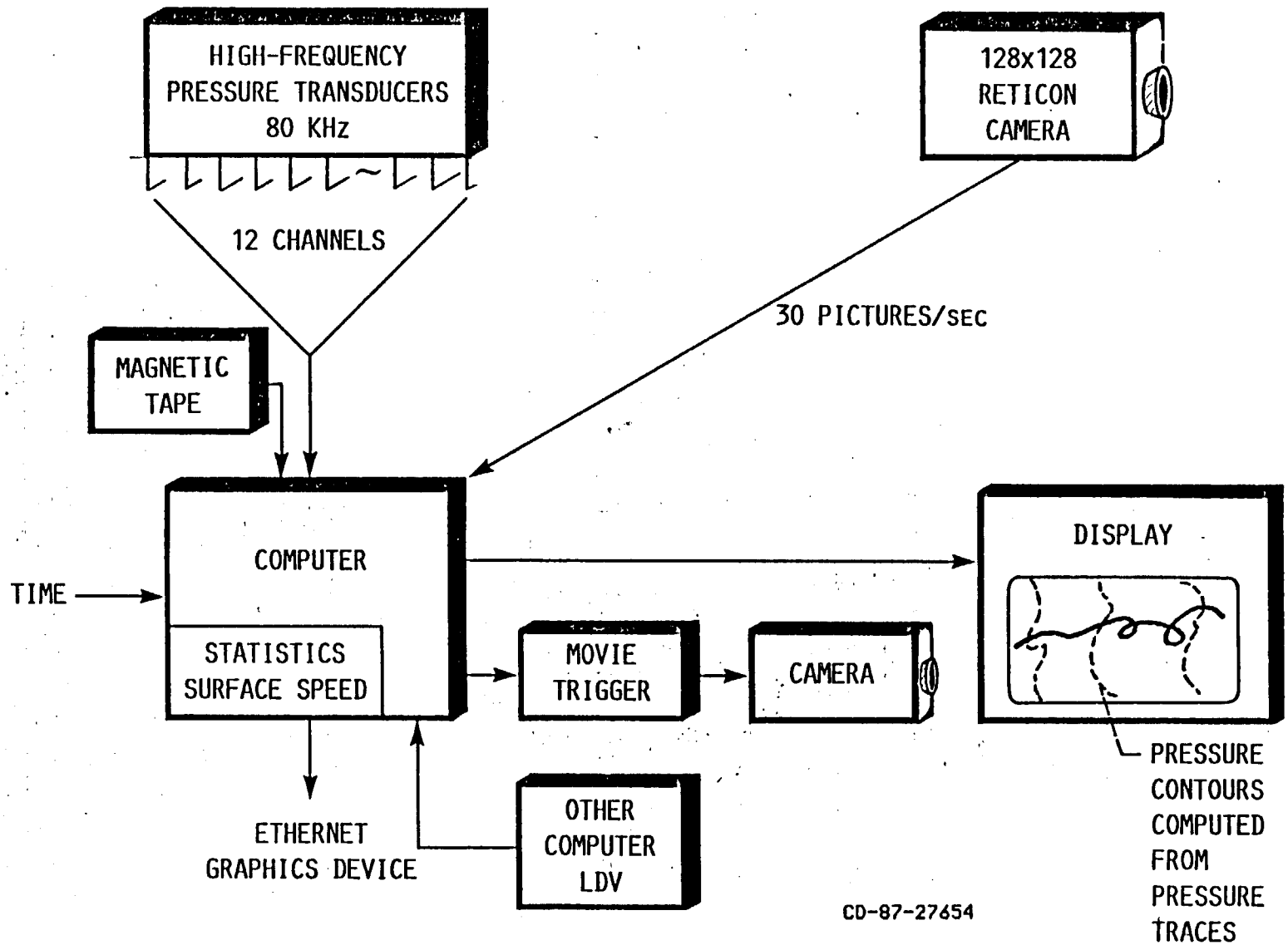
CD-87-27648

PLANAR COMPRESSIBLE REACTING SHEAR LAYER

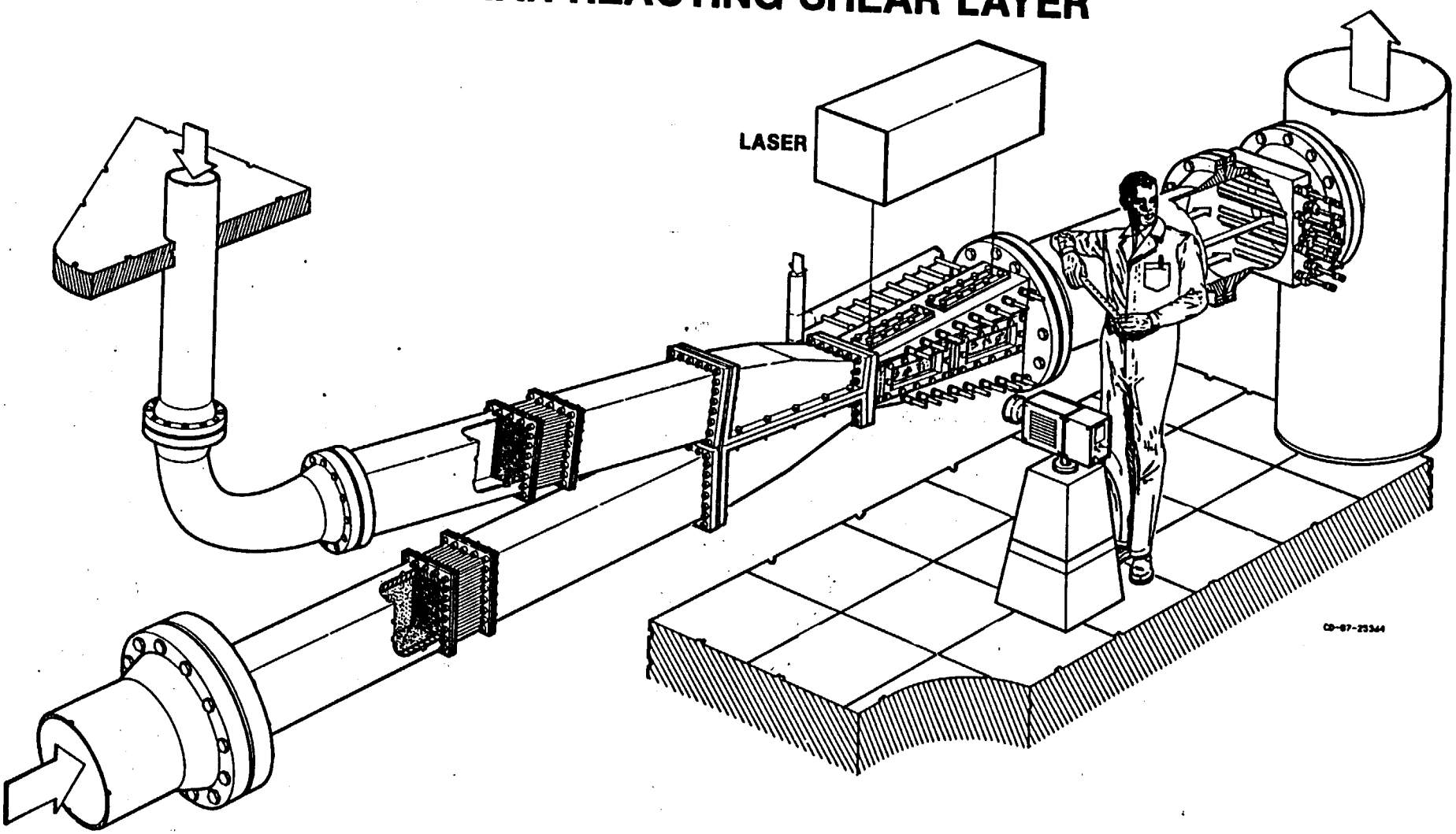
KEY EXPERIMENTAL FEATURES

- Continuous flow capability
- Subsonic, compressible flows (100–300 m/sec)
- High non–vitiated air preheat (≤1200 °F)
- High heat release appropriate for propulsion

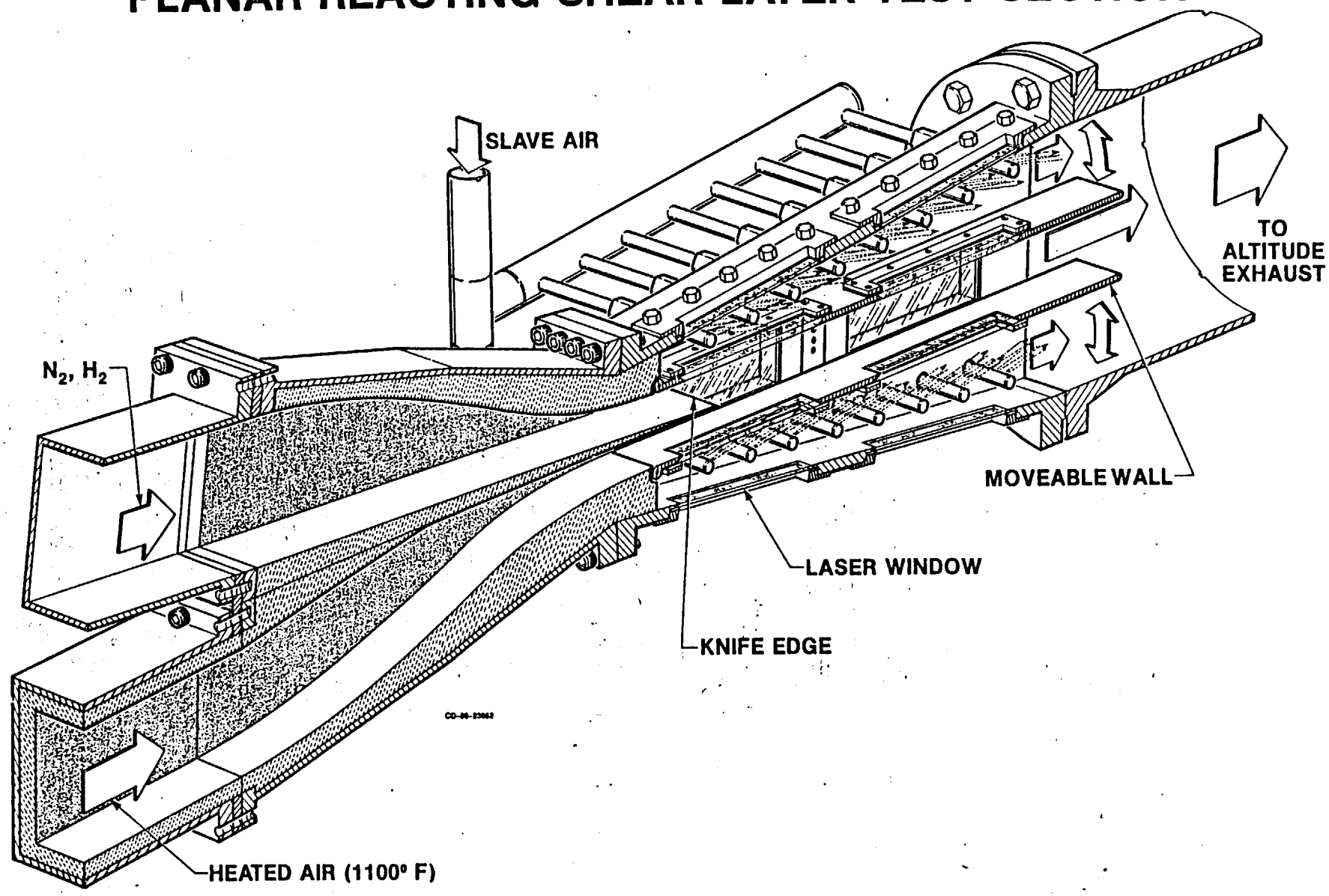
PLANAR COMPRESSIBLE REACTING SHEAR LAYER



PLANAR REACTING SHEAR LAYER



PLANAR REACTING SHEAR LAYER TEST SECTION



PLANAR COMPRESSIBLE REACTING SHEAR LAYER

KEY STAFF	AFFILIATION	EXPERTISE/RESPONSIBILITY
Dr. C. J. Marek	NASA	Principal Investigator
Dr. K. Radhakrishnan	Sverdrup	Chief Code Developer
Dr. C. Wey	Sverdrup	Laser Diagnostics
Dr. J. Miles	NASA	Fluid Mechanics, Acoustics
Prof. J. T'ien	C—WRU	Combustion
Prof. B. Ghorashi	CSU	Flowfield Image Analysis

CONSULTANTS		
Mr. R. Claus	NASA	DNS With Combustion
Dr. J—S Shuen	Sverdrup	Combustion CFD

AMES RESEARCH CENTER, NASA
FIRST WORKSHOP ON CODE VALIDATION

THE VALIDATION OF NUMERICAL COMPUTATIONS

Air Force Wright Aeronautical Laboratories

Melvin L. Buck

Assistant for Experimental Simulation

Aeromechanics Division

Richard D. Neumann

High Speed Aero Performance Branch

JULY 1987

N92-70940

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WHAT CONSTITUTES CODE VALIDATION ?

* WHEN DO WE ACHIEVE VALIDATION ?
  - CODE OUTPUT AGREES WITH VALIDATION STANDARD ?
  - CODE OUTPUT IS INSENSATIVE TO INCIDENTIAL FEATURES OF COMPUTATION ?

* HOW DO WE VALIDATE ?
  - STRESS THE CODE ?
  - MATCH THE CONFIGURATION DETAILS ?

* WHAT ABOUT A LACK OF AGREEMENT ?
  - IS THE VALIDATION STANDARD CORRECT ?
  - IS THE COMPUTATION CORRECTLY MADE ?

TYPES OF VALIDATION REQUIRED

DATA BASE
(OR VALIDATED STD.)
TEST CASES FOR NEW
CORPORATE USER

P.N.S. WORKSHOP
1986 TEST CASES?

NEEDED
NATIONAL EFFORT
IN EXPERIMENTAL
CODE VALIDATION

SPECTRUM OF BENCHMARK
DATA ON EXAMPLES WHICH
ILLUSTRATE POTENTIAL APPLICATIONS
(DELTA WINGS)
(HEAVY LIFT BOOSTERS)

BOGDENOFF/KNIGHT/
HORSTMANN
ACTIVITY

STUDIES OF 3D INTERACTIONS
SUITABLE FOR VALIDATING
ONLY FULL N.S. SOLUTIONS
STRESSING TURBULENCE MODELS

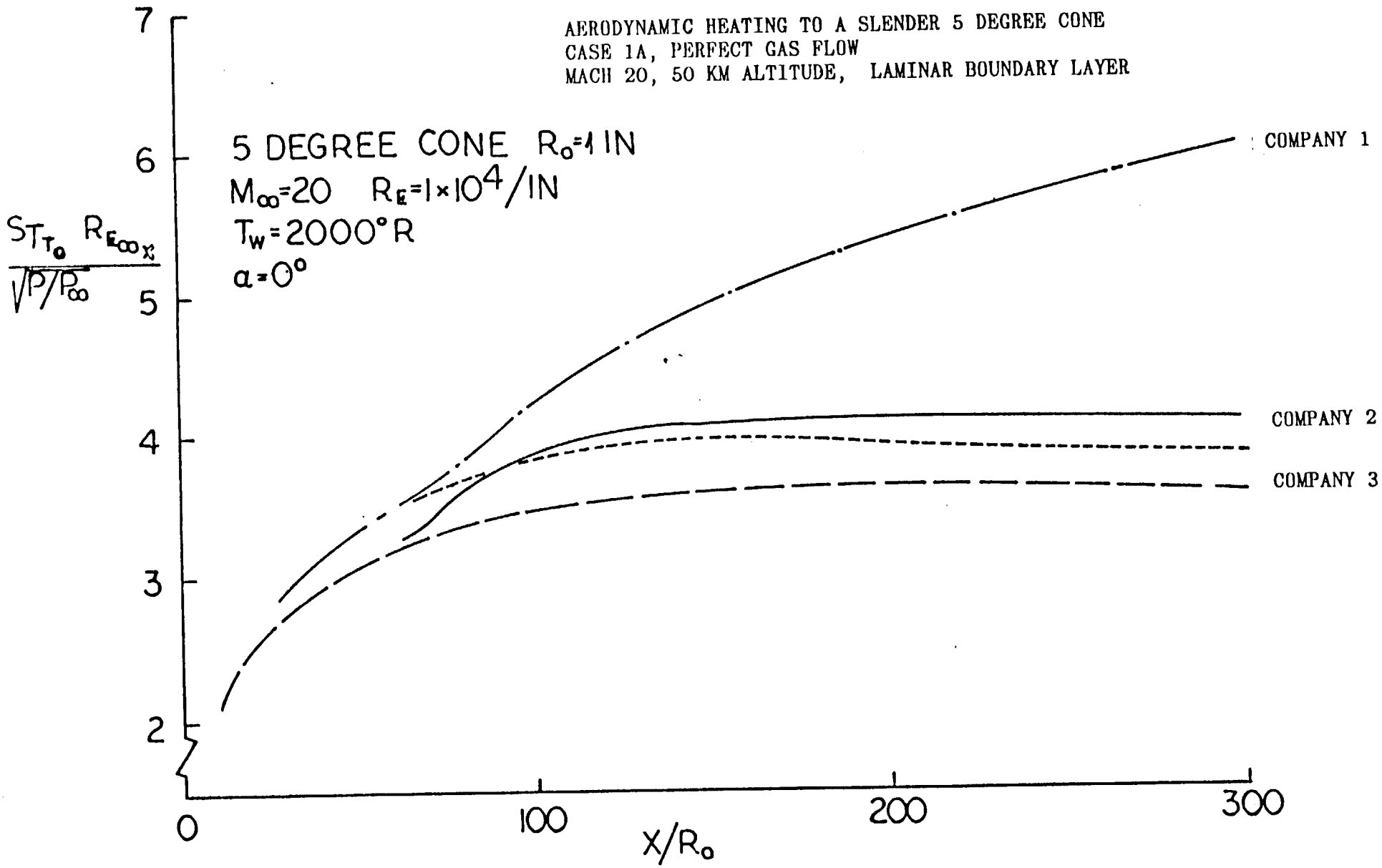
THE PARAMETERS OF VALIDATION REQUIRED DIFFER WITH THE TYPE OF CASE (PNS/NS ETC.) AND WITH THE INTENDED APPLICATION (TURBULENT/LAMINAR,ETC.)

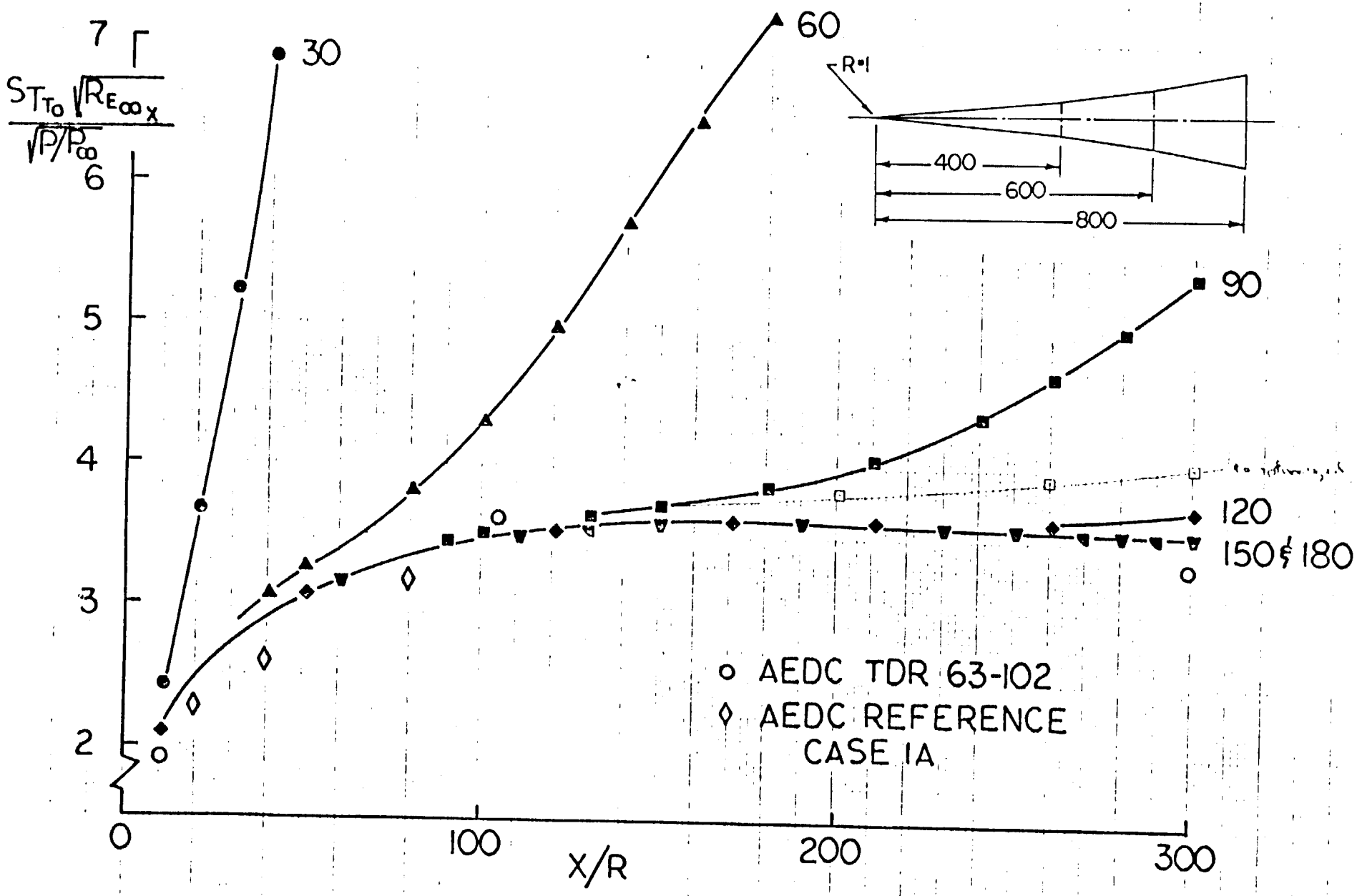
* WE CHALLENGE THAT EXPERIENCED CORPORATE USERS CAN ACCURATELY GENERATE CONICAL BODY DATA AT ZERO ANGLE OF ATTACK
* THERE ARE MANY PROPOSED VALIDATION EXPERIMENTS THAT ARE SO HIGHLY TAILORED THAT ONLY FULL N.S. CODES CAN BE USED
  - - - GREAT FOR RESEARCH / BAD FOR DESIGN
* THERE IS A LARGE CLASS OF PROBLEMS THAT REQUIRE NO TURBULENCE MODEL SPECIFICATION - THEY STRESS THE CODES AT THE LOW DENSITY LIMIT
* MANY OF THE SO CALLED HIGH REYNOLDS NUMBER EFFECTS ARE DUE TO POOR GRID DEFINITION RATHER THAN TURBULENCE MODEL LIMITS.

* * * * * * * * * * * * * * *

MUST CONSIDER A SPECTRUM OF POSSIBLE CODES AND POSSIBLE APPLICATIONS IN ANY PROPOSED VALIDATION PROGRAM.

AERODYNAMIC HEATING TO A SLENDER 5 DEGREE CONE
CASE 1A, PERFECT GAS FLOW
MACH 20, 50 KM ALTITUDE, LAMINAR BOUNDARY LAYER



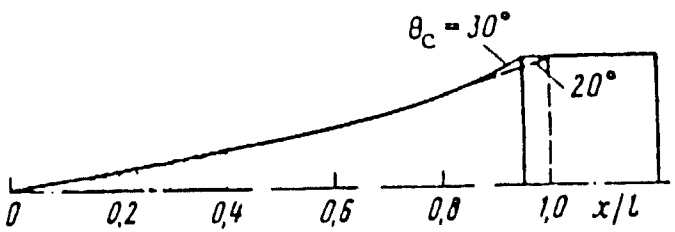

$\frac{S_{T_{T_0}}\sqrt{R_{E_{\infty x}}}}{\sqrt{P/P_\infty}}$
7
6
5
4
3
2
0
100
200
300
X/R
30
60
90
120
150 & 180
R=1
400
600
800
AEDC TDR 63-102
AEDC REFERENCE CASE IA

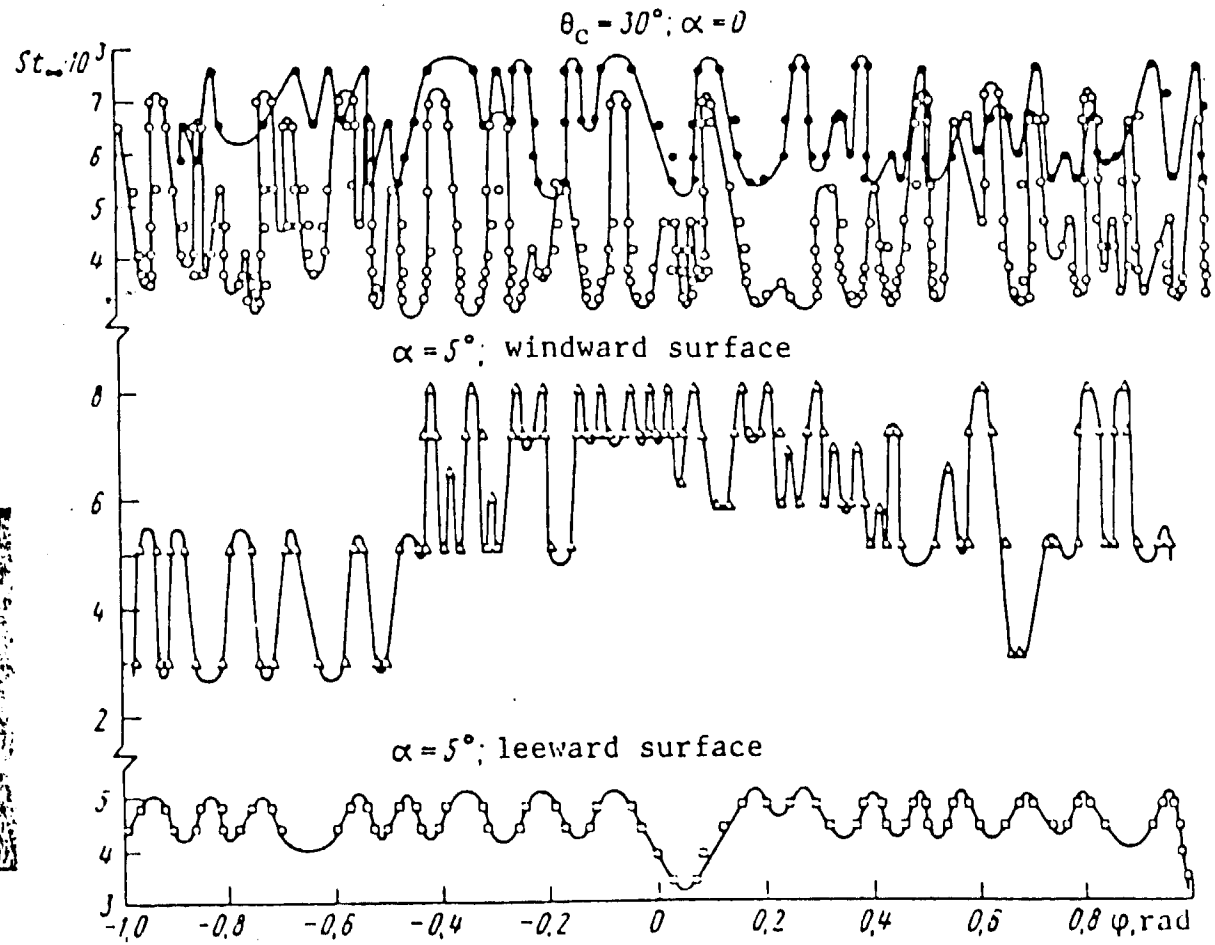
FLUID MECHANICS-Soviet Research, Vol. 15, No. 4, July-August 1986

Heat Transfer on Cones with Isentropic Compression Surface*

V. N. BRAZHKO AND N. N. SHKIRIN

Zhukovskiy Institute of Aerohydrodynamics





FLOWFIELD VALIDATION MUST NOT ONLY GENERATE DATA SENSATIVE TO CODE VALIDATION BUT ALSO CRITICAL DATA AT TEST CONDITIONS WHICH STRESS CODE MODELING ASSUMPTIONS

WE CAN NOT JUST VALIDATE IN "EASY","FAST" FACILITIES.
WE MUST QUESTION THE CODING AT THE LIMITS OF ASSUMPTIONS.

* CONTINUUM:
* HIGH REYNOLDS NUMBER:
* REAL GAS:

FROM THE STANDPOINT OF NUMERICS, VALIDATION REQUIRES THAT WE UNDERSTAND AND CRITICALLY BOUND EACH AND EVERY MODEL EMPLOYED IN THE NUMERICAL APPROACH

* MODELS ARE VALID ONLY OVER SPECIFIC REGIONS

  THIS INFORMATION IS LOST ON THIRD PARTY USERS.

  RANGES OF MODEL VALIDITY SHOULD BE CLEARLY STATED BY THE DEVELOPER

* * * * * * * * * * * *

CRITERIA EMERGING ON CELL SIZE, ASPECT RATIO, AND REYNOLDS NUMBER SHOULD BE QUANTIFIED AND PLACED IN CODES AS ADVISORY COMMENTS.

VALIDATION OF TURBULENT DATA

EXPERIMENTALLY – TOUGH TO ACCOMPLISH VALIDATION DATA.

MUST ... ELIMINATE TRIP MECHANISMS – OR – START THE CODE FROM EXPERIMENTAL DATA IN AN EQUILIBRIUM BOUNDARY LAYER

COMPUTATIONALLY – TOUGH TO GENERATE DATA (MECHANICALLY) AS REYNOLDS NUMBER GETS VERY LARGE (AND BOUNDARY LAYER THICKNESS VERY SMALL)

– DOES TURBULENCE MODEL ACCOUNT FOR IMMATURE TURBULENT FLOW? IMPLICATIONS FOR TEST AND COMPARISONS.

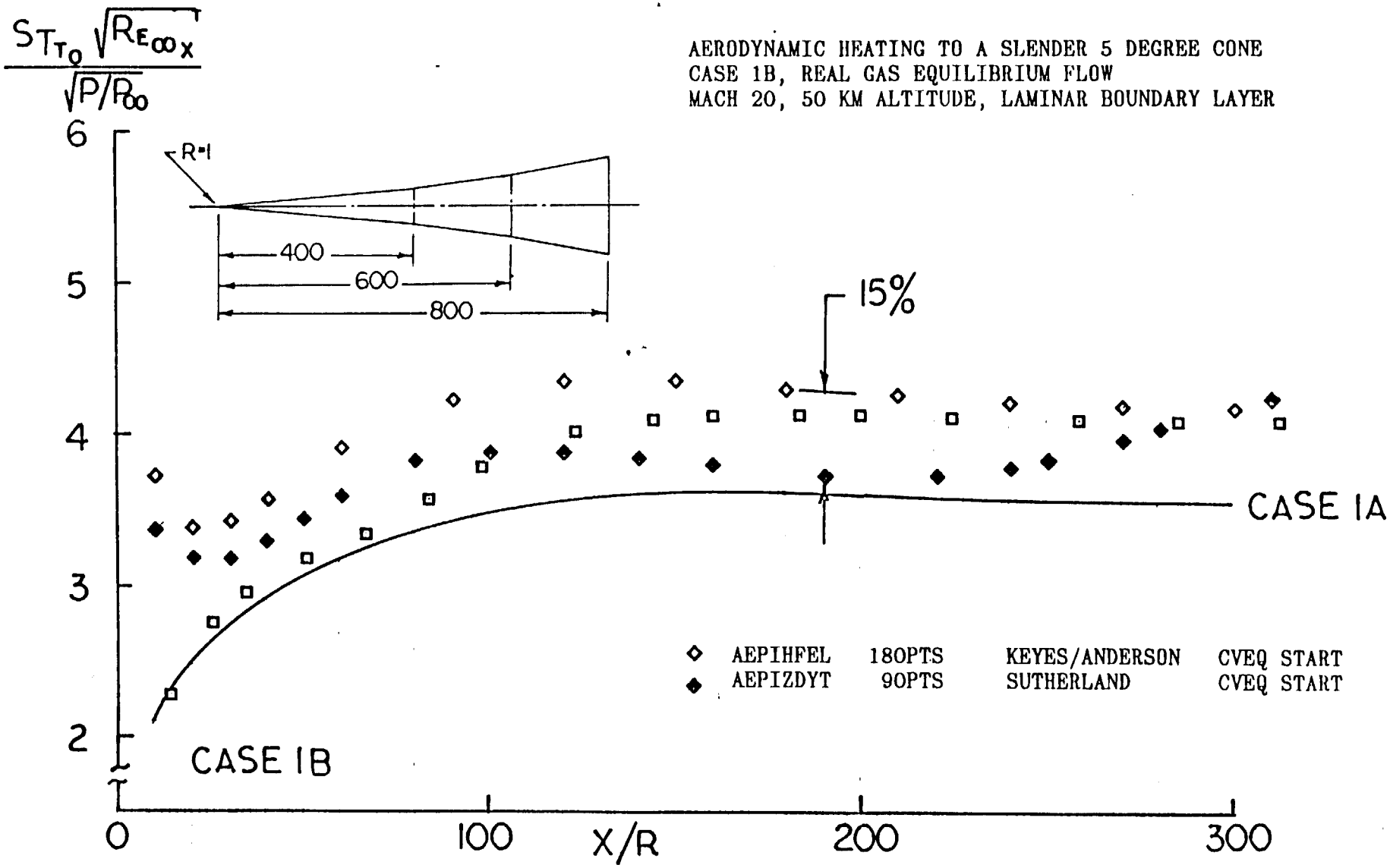
THERMODYNAMIC AND TRANSPORT PROPERTIES MUST BE CORRECTLY MODELED IN THE NUMERICAL APPROACH

- REPLACE, FOR EXAMPLE, SUTHERLAND VISCOSITY MODEL AS $T \rightarrow 100^{\circ}R$ AND AS $T \rightarrow 10\,000^{\circ}$ WHAT IS A VERY HIGH TEMPERATURE "PERFECT GAS"

- SEPARATE THERMODYNAMIC AND TRANSPORT MODELS FOR GROUND TEST AND FREE FLIGHT
- MODEL STANDARDIZATION ?

* * * * * * * * * * * * * * * * *

BEFORE WE CAN HOPE TO VALIDATE COMPUTER CODES WE MUST CLEAN UP THE POOR INTERNAL MODELING WITHIN THE CODES AND THE PRACTICE OF CONSTANT TWEAKING WITHIN MODELS


AERODYNAMIC HEATING TO A SLENDER 5 DEGREE CONE
CASE 1B, REAL GAS EQUILIBRIUM FLOW
MACH 20, 50 KM ALTITUDE, LAMINAR BOUNDARY LAYER
$\frac{St_{T_0}\sqrt{Re_{\infty x}}}{\sqrt{P/P_\infty}}$
R=1
400
600
800
15%
CASE 1A
CASE 1B
AEPIHFEL 180PTS KEYES/ANDERSON CVEQ START
AEPIZDYT 90PTS SUTHERLAND CVEQ START
6
5
4
3
2
0
100
200
300
X/R

REAL GAS CODE VALIDATION

THE CODES TO BE VALIDATED MUST BE CAPABLE OF HANDLING FLOW CHARACTERISTICS "PECULIAR" TO TEST FACILITIES.

* NON UNIFORM TEST FLOWS – SOURCE FLOW EFFECTS AND NON UNIFORM NOZZLE EXIT CONTOURS.

* A FREESTREAM BOUNDARY CONDITION HAVING GAS CONSTITUENTS FAR REMOVED FROM FREE FLIGHT AIR.

* TEST GASES RADICALLY DIFFERENT FROM "AIR" IN FLIGHT

FLIGHT DYNAMICS LABORATORY (FIM) VALIDATION EFFORTS

* CURRENT P.N.S. WORKSHOP CODE TO CODE VALIDATION EFFORT (TO BE PRESENTED IN SEPTEMBER)

* REAL GAS CODE VALIDATION CONTRACT EFFORT (NO AWARD TO DATE)

* EXPERIMENT/NUMERICAL COMPARISON FOR DELTA WING FLOWS AT HIGH ANGLE OF ATTACK (JOE SHANG)

* * * * * * * * * * * * * *

WE BELIEVE THAT INHERENTLY CODE VALIDATION IS A RESPONSIBILITY OF THE GOVERNMENT LABORATORIES.

1987 PNS WORKSHOP COMPUTATIONAL CASES

Cases 1a and 1b

1) Geometry shown .

2) Nose radius = 1. in.

3) Angle of attack = 0 deg.

4) Mach number = 20.

5) Altitude = 50 km. (164,050 ft)

6) Flow type; laminar over the entire length

7) Wall temperature = 2,000 Rankine

8) Gas model; Case 1a is a perfect gas

Cases 2a and 2b

1) Geometry shown .

2) Nose radius = 1. in.

3) Angle of attack = 0 deg.

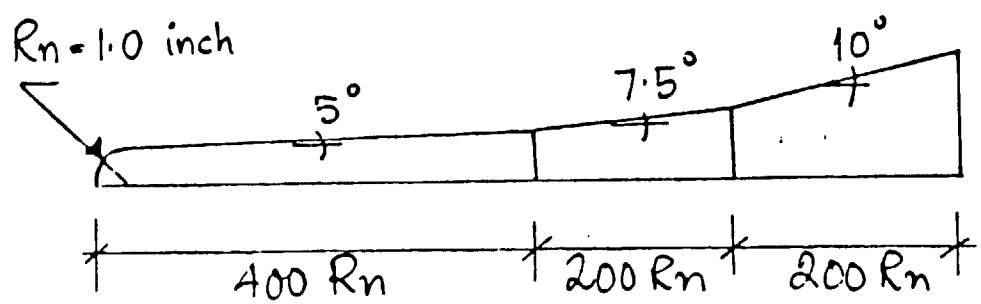
4) Mach number = 20.

5) Altitude = 100,000 ft.

6) Flow type; laminar up to x/r_n = 10.
then transition instantaneously to turbulent flow

7) Wall temperature = 2,000 Rankine

8) Gas model; Case 2a is a perfect gas
Case 2b is an equilibrium real gas



5°-7.5°-10° Tricone

1987 PNS WORKSHOP COMPUTATIONAL CASES

Cases 3a and 3b

1) A spherically blunted 5^0 cone with a lenght of 800 nose radii.

2) Nose radius = 0.1 in.

3) Angle of attack = 5 deg.

4) Mach number = 20.

5) Altitude = 100,000 ft.

6) Flow type; laminar over the entire length

7) Wall temperature = 2,000 Rankine

8) Gas model; Case 3a is a perfect gas
Case 3b is an equilibrium real gas

Cases 4a and 4b

1) Geometry shown
cone-cylinder flare.

2) Nose radius = 6. in.

3) Angle of attack = 0 deg.

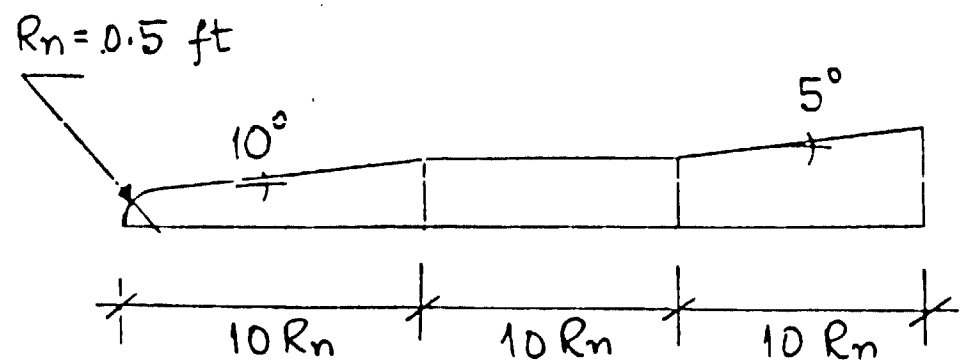
4) Mach number = 25.

5) Altitude = 275,000 ft.

6) Flow type; laminar over the entire length

7) Wall temperature = 2,000 Rankine

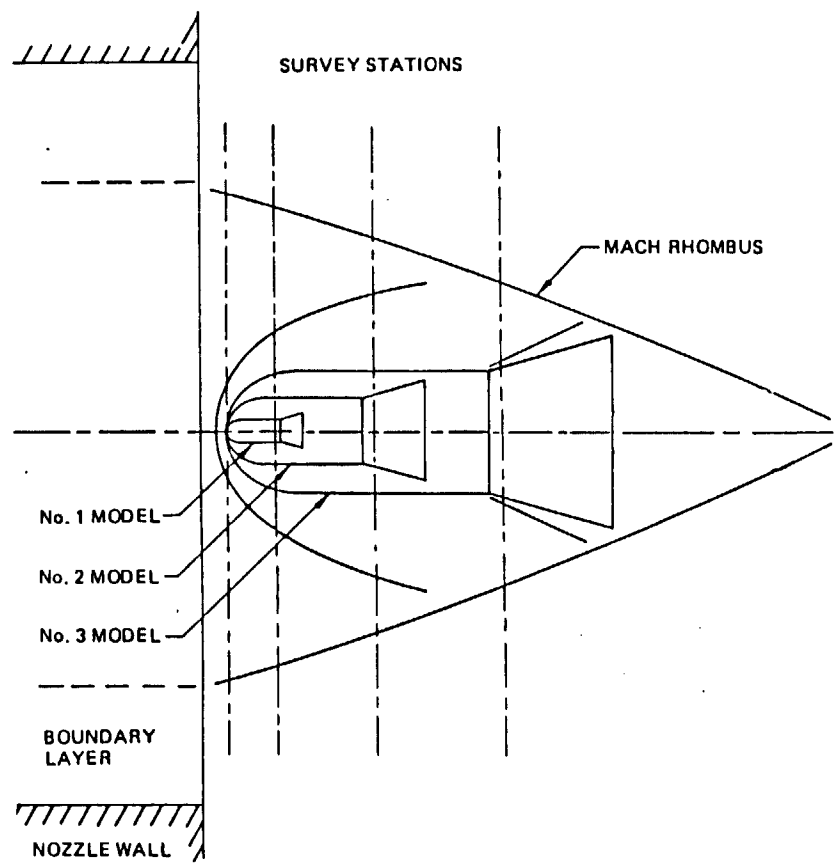
8) Gas model; perfect gas



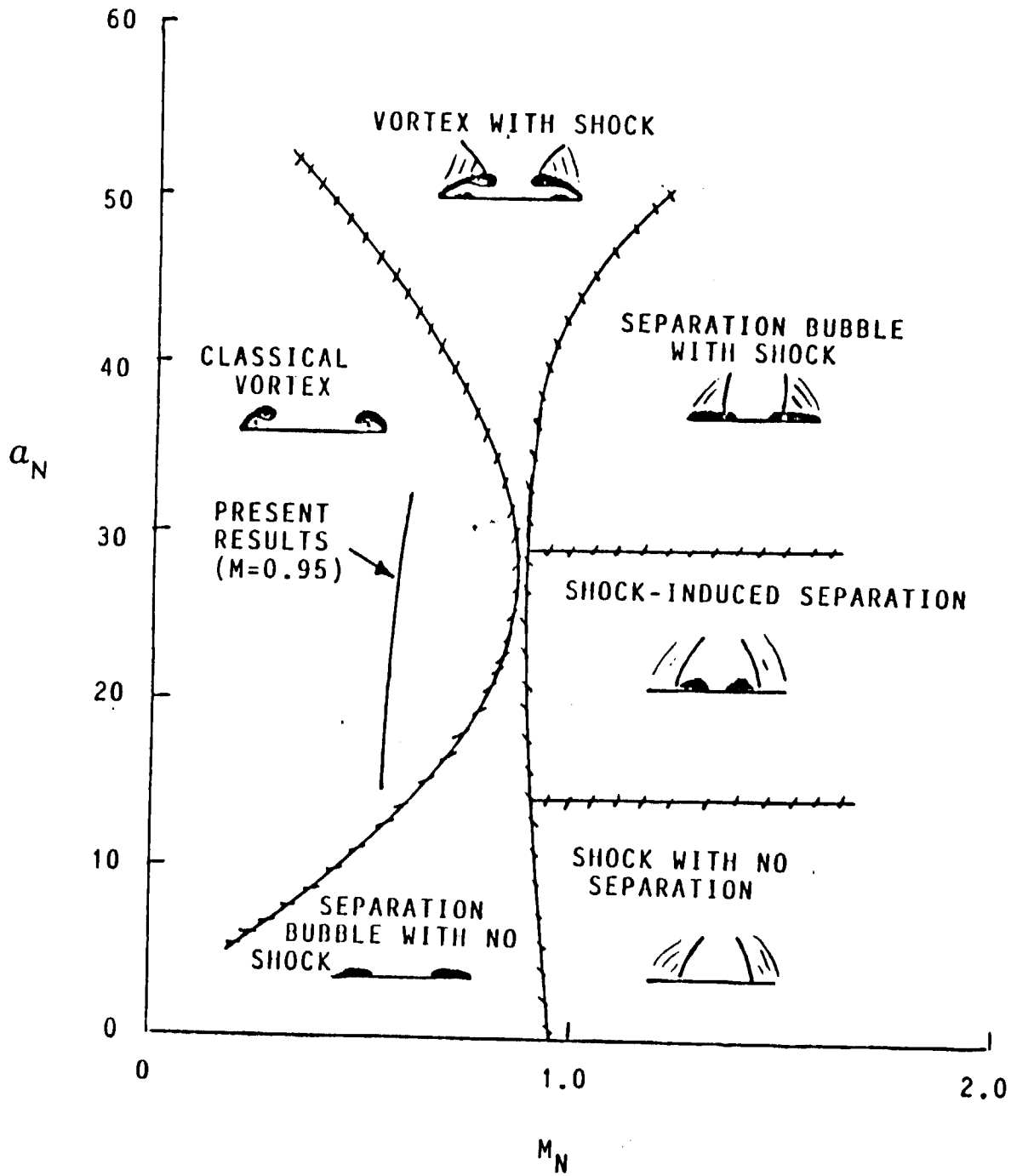
Reacting Gas Experimental Data In Low Density Flow

FEATURES OF PROGRAM

* SUFFICIENT VELOCITY TO DISSOCIATE AIR
* UNIQUE STATE OF THE ART REAL GAS INSTRUMENTATION
* MODEL GEOMETRY THAT ACCENTUATES REAL GAS PHENOMENA
* PARALLEL NUMERICAL AND EXPERIMENTAL ACTIVITIES FROM NOZZLE THROAT
* EXAUSTIVE STUDY AT ONE TEST POINT



MILLER AND WOOD (1983)



CURRENT CFD EFFORTS IN PROJECTILE AERODYNAMICS

CHARLES J. NIETUBICZ

presented at

FIRST NASA CFD VALIDATION WORKSHOP
JULY 14-16, 1987

N92-70941

OUTLINE

- CFD WORK AREAS
- INVISCID / VISCOUS CODES
- CURRENT APPLICATIONS
- EXPERIMENTAL DATA REPORTED
- COMPUTATIONAL STUDIES REPORTED

CFD WORK AREAS IN PROJECTILE AERODYNAMICS

- SPINNING PROJECTILES

  BLUNT NOSE
  ROTATING BANDS
  INTERNAL FLOW
  BASE FLOW W/BLEED

- FIN STABILIZED PROJECTILES

  NON–DEFLECTING FINS
  DEFLECTING FINS
  LONG L/D
  BODY GROOVES
  AERODYNAMIC HEATING

COMPUTER CODES CURRENTLY IN USE (CONTINUED)

VISCOUS FLOW MODELING

- PARABOLIZED NAVIER-STOKES PNS

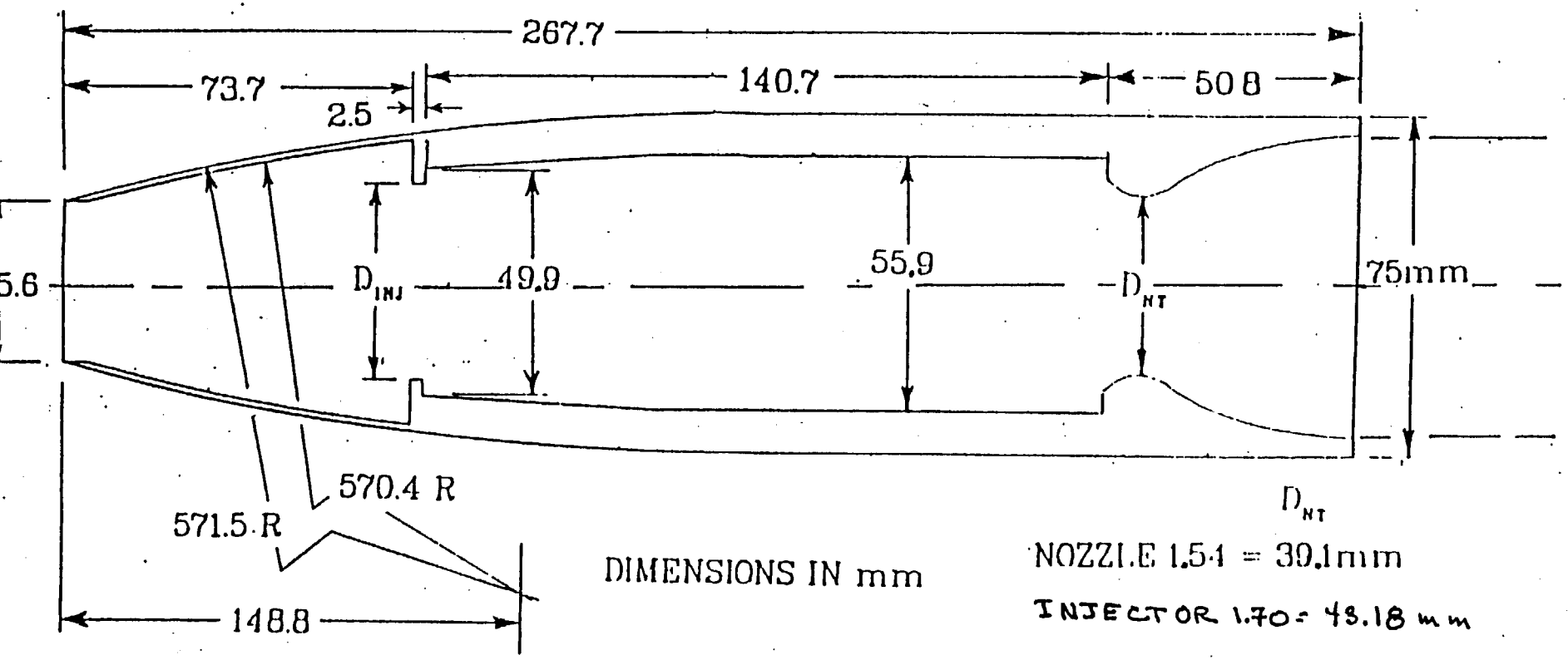
  SCHIFF-STEGER IMPLICIT 3D CODE, SUPERSONIC FLOW, BODIES OF REVOLUTION INCLUDING AFT FINS ALIGNED WITH THE BODY AXIS

- UNSTEADY NAVIER-STOKES

  PULLIAM-STEGER IMPLICIT 3D CODE, TRANSONIC AND SUPERSONIC FLOW, BODIES OF REVOLUTION INCLUDING BASE FLOW MODELING

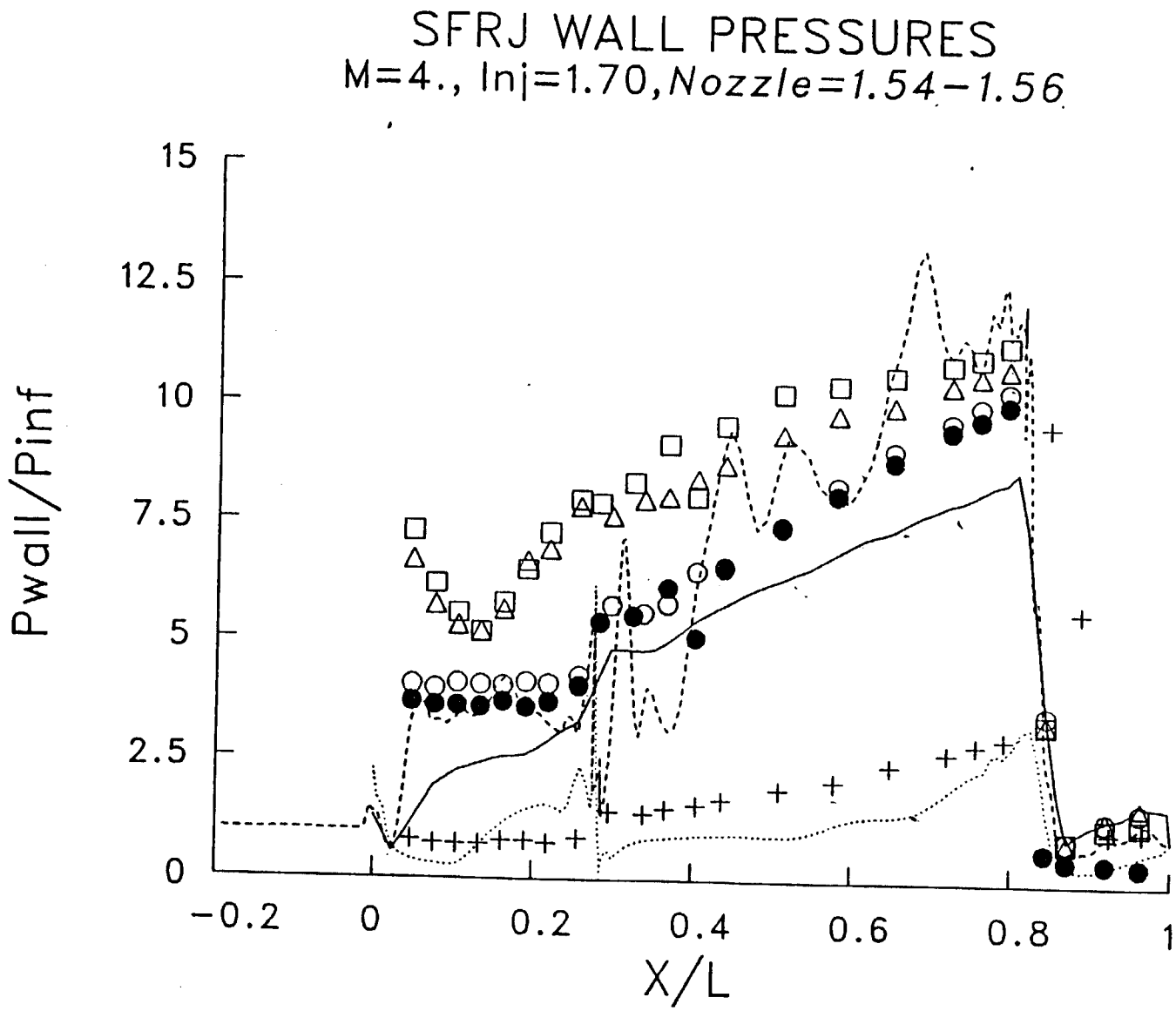
- AXISYMMETRIC NAVIER-STOKES

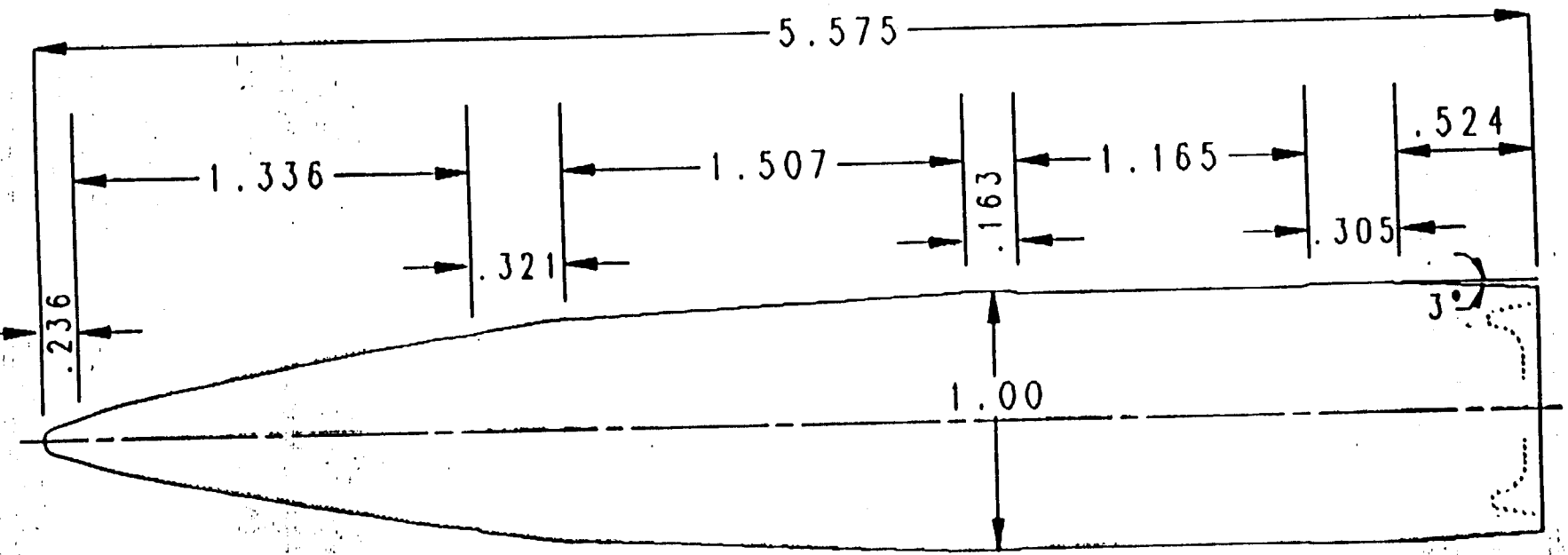
  PULLIAM-STEGER-NIETUBICZ GENERALIZED 2D CODE FOR BODIES OF REVOLUTION INCLUDING BASE FLOW MODELING



DIMENSIONS IN mm

MODEL GEOMETRY

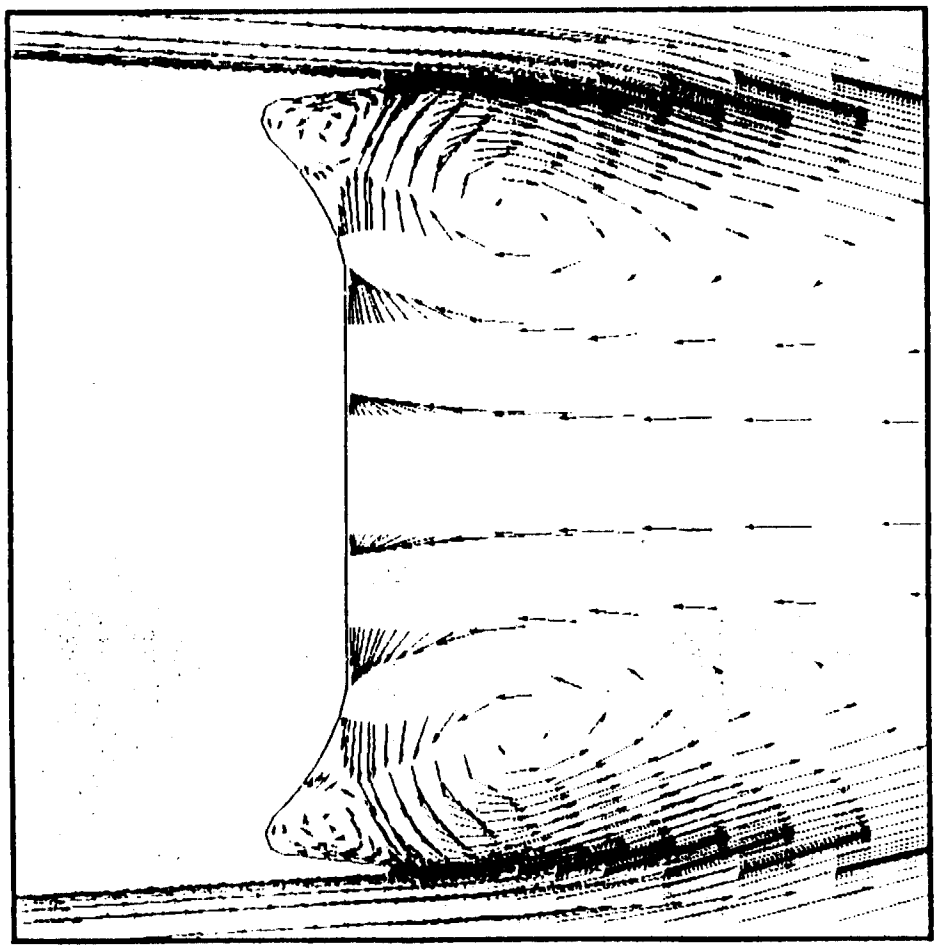

SFRJ WALL PRESSURES
M=4., Inj=1.70, Nozzle=1.54-1.56
Pwall/Pinf
15
12.5
10
7.5
5
2.5
0
-0.2
0
0.2
0.4
0.6
0.8
1
X/L



ALL DIMENSIONS
ARE IN CALIBERS
(1 cal = 6.09 in.)

COMPUTATIONAL MODEL OF THE XM864 BASE BLEED

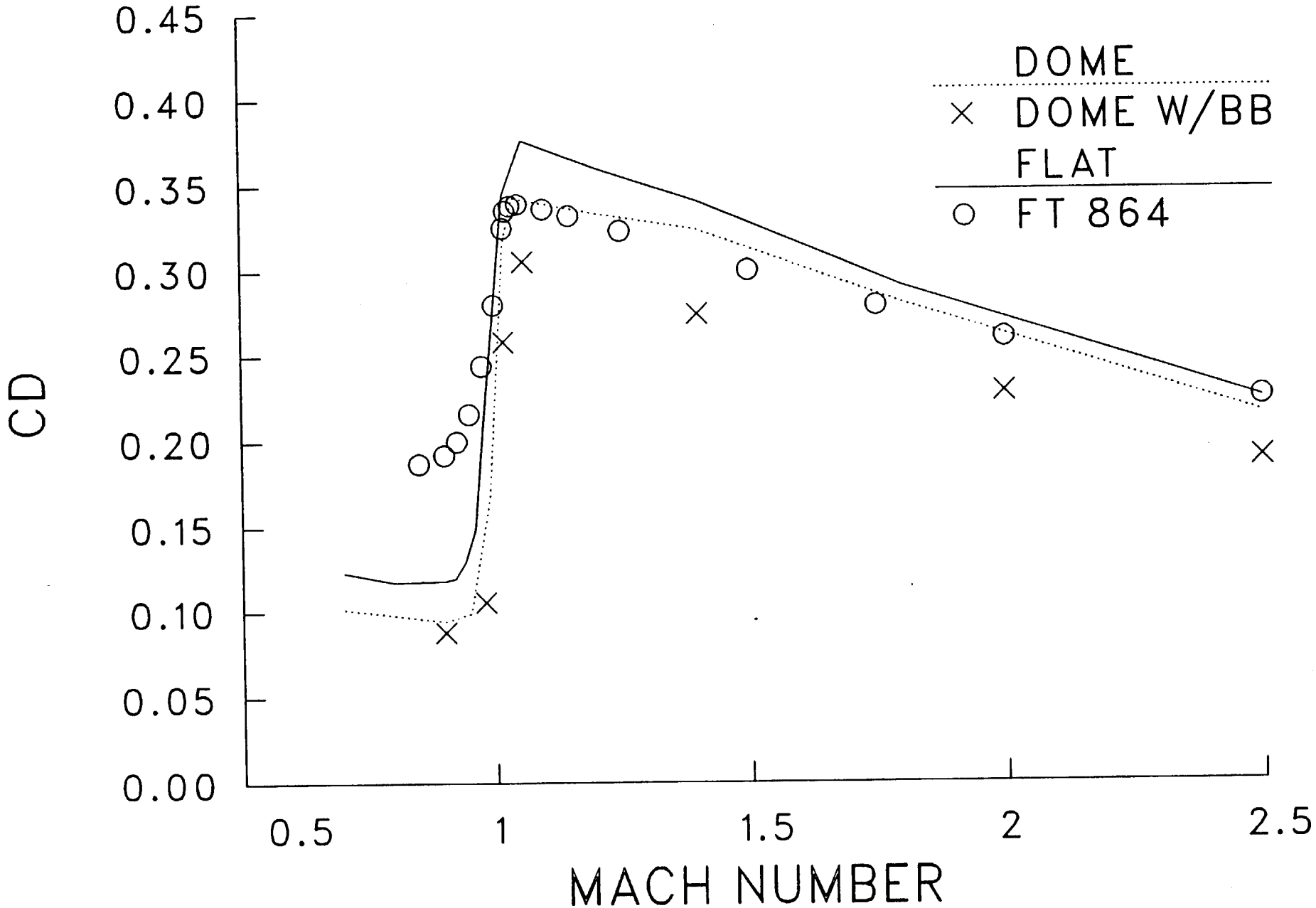
VELOCITY



1.400	M_∞
0.00°	α
4.91×10^6	Re
205×60	GRID 1
205×60	GRID 2
60×60	GRID 3
60×60	GRID 4

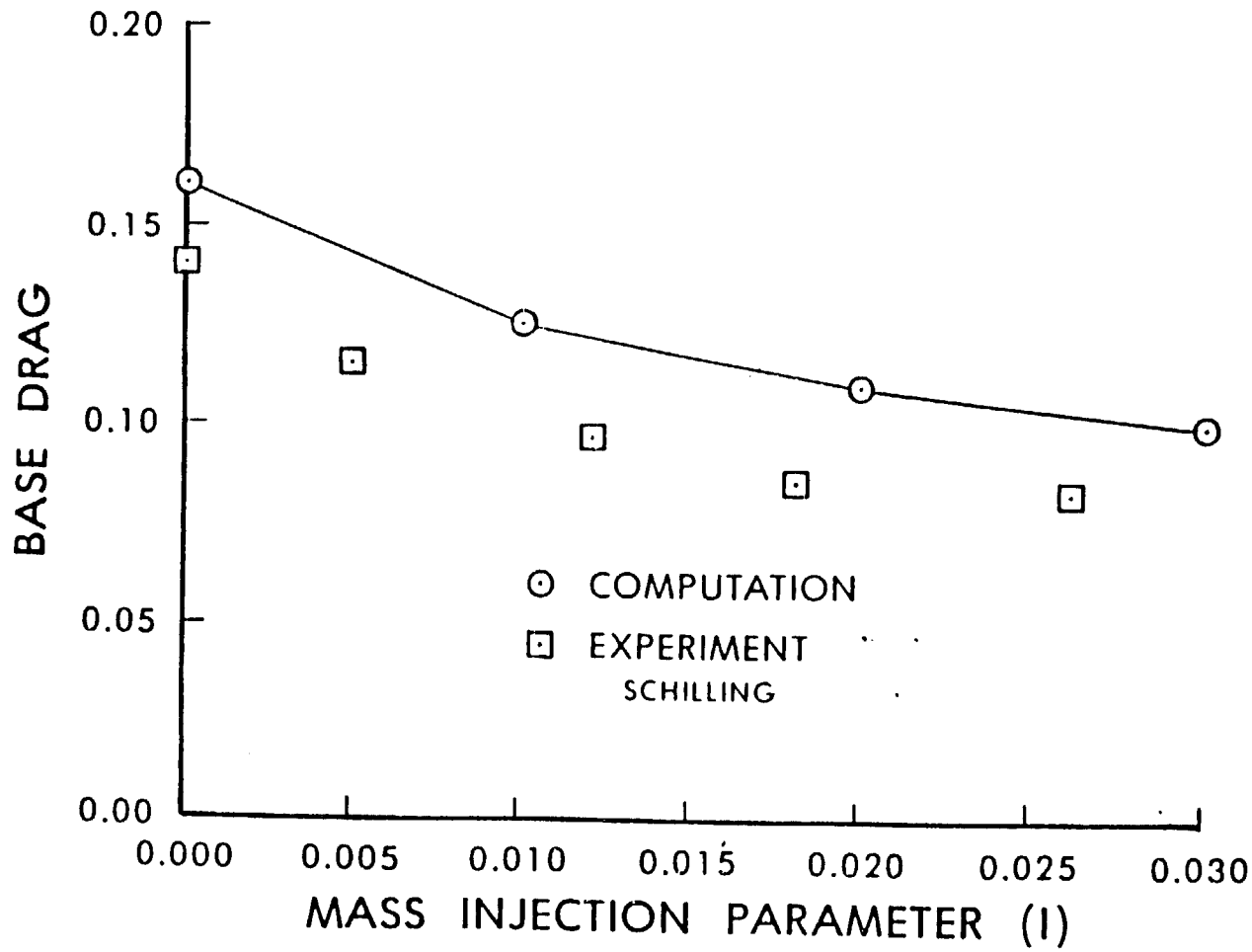
PLOT 10 15:27:30 MON 1 JUN, 1987 JOB-HEAVEY , ISSCO DISSPLA 10.0

X.M864


0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
CD
0.5
1
1.5
2
2.5
MACH NUMBER
DOME
DOME W/BB
FLAT
FT 864

VARIATION OF BASE DRAG WITH BASE BLEED

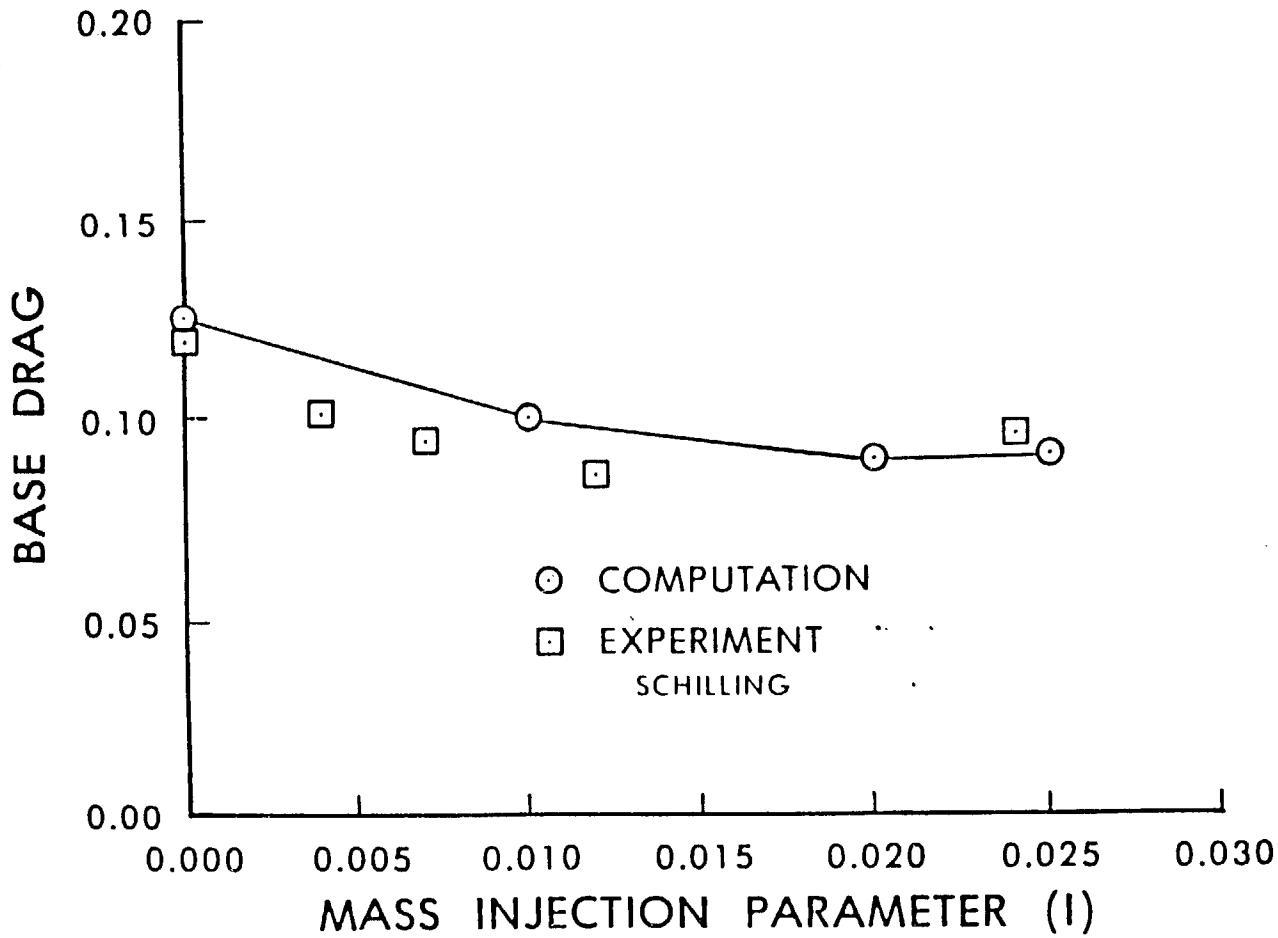
$M = 1.7, \quad \alpha = 0$



DEC 85

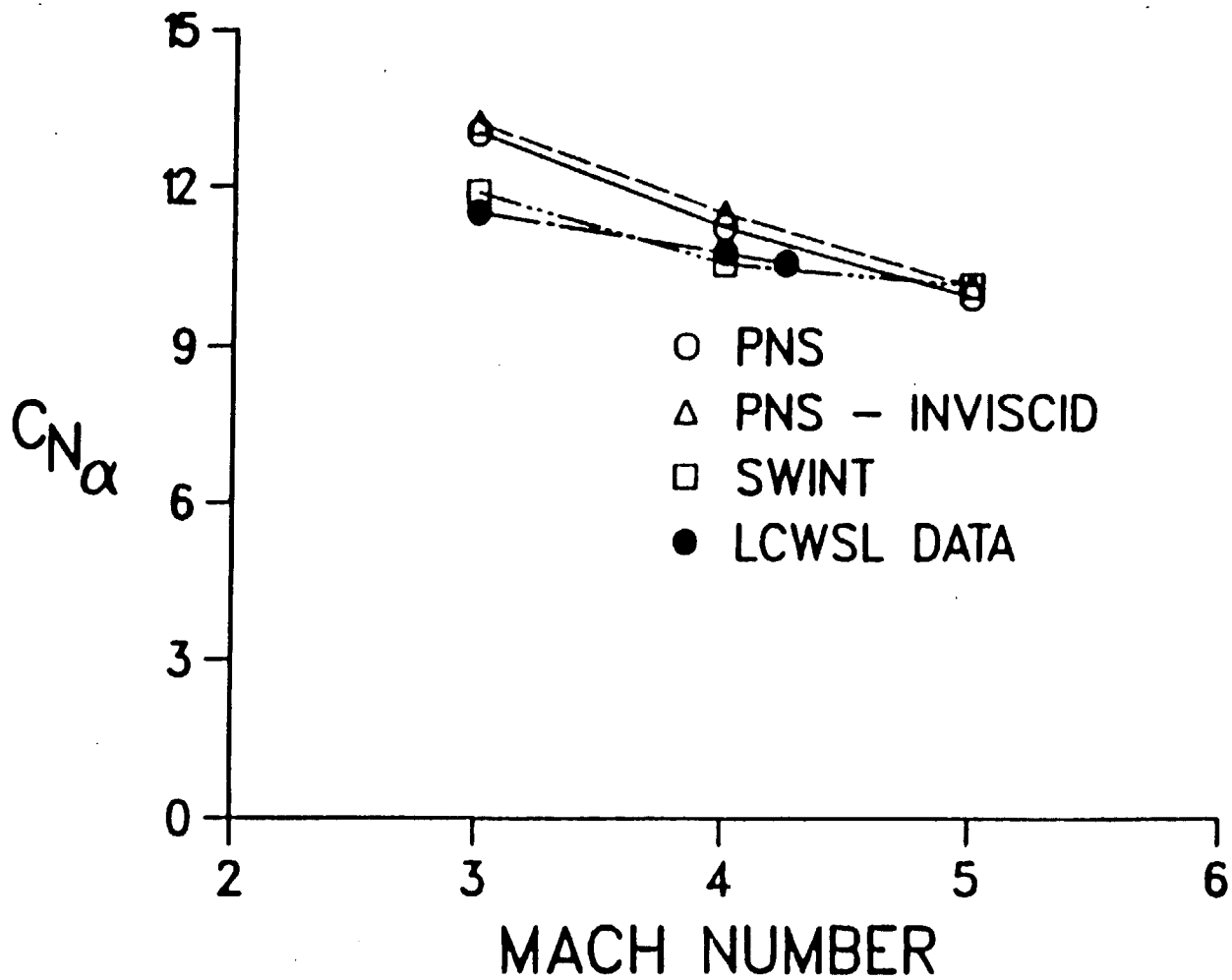
VARIATION OF BASE DRAG WITH BASE BLEED

$M = 2.5, \quad \alpha = 0$



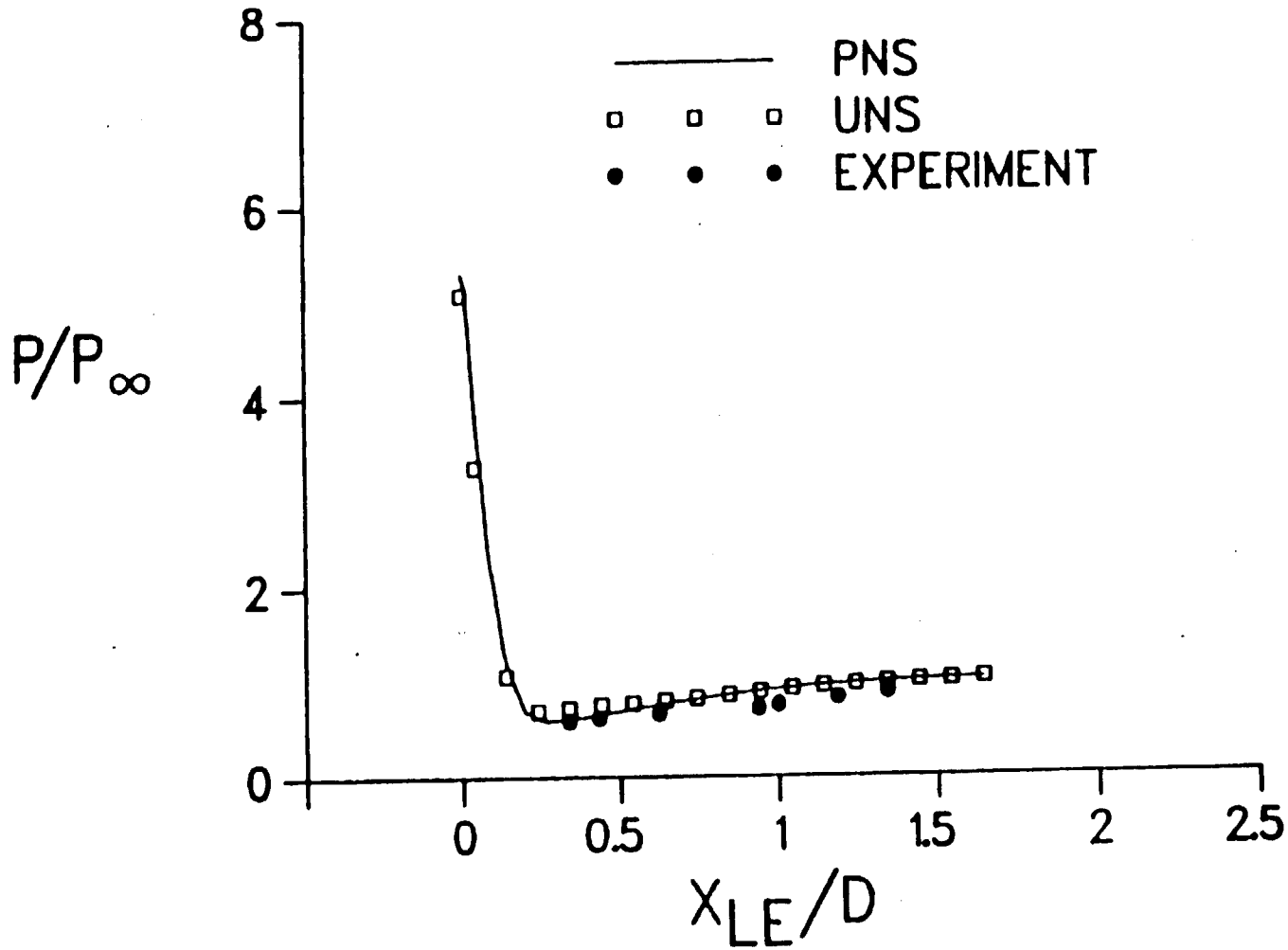
DEC 85

VARIATION OF NORMAL FORCE WITH MACH NUMBER



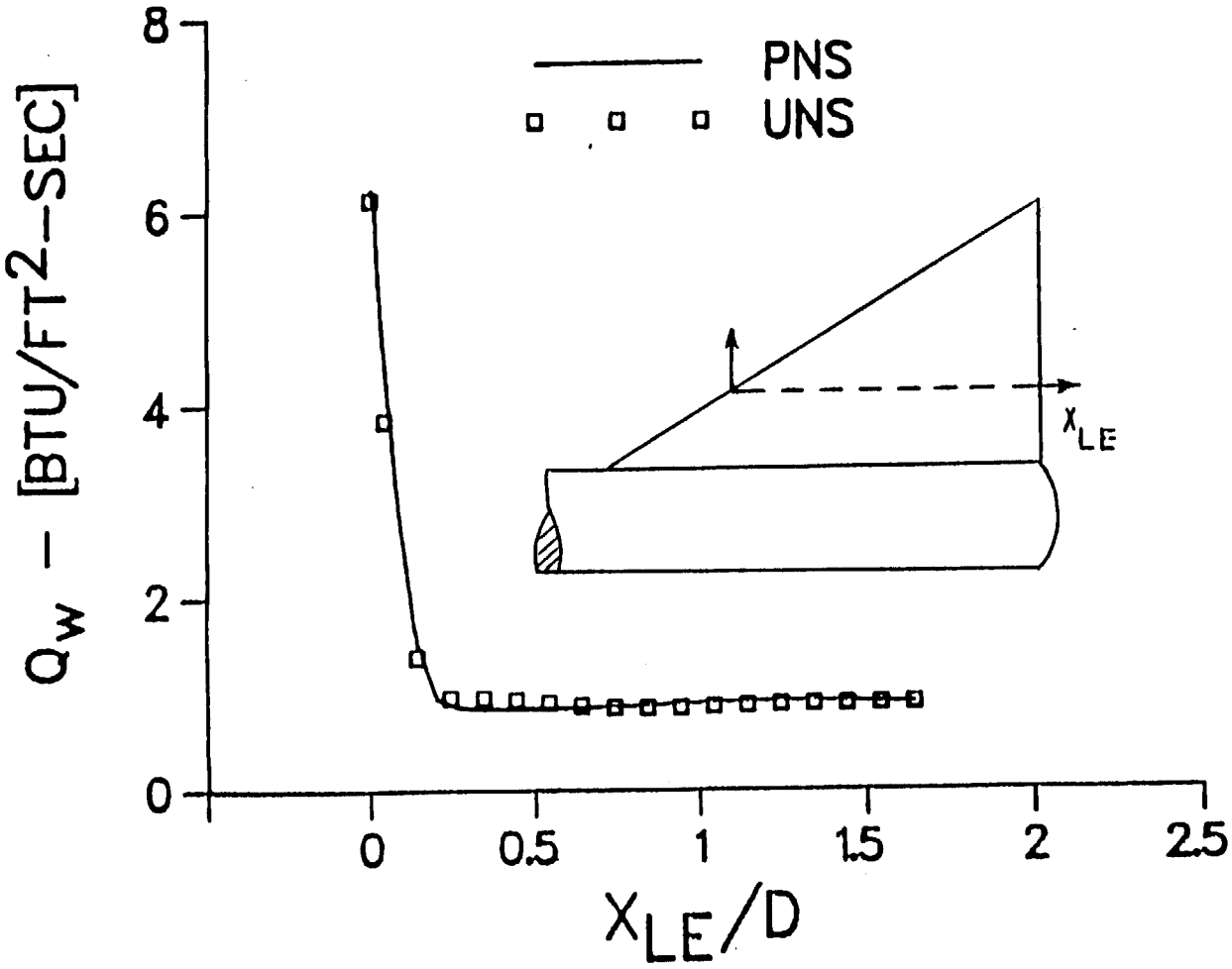
CHORDWISE PRESSURE DISTRIBUTION – SECTION 3

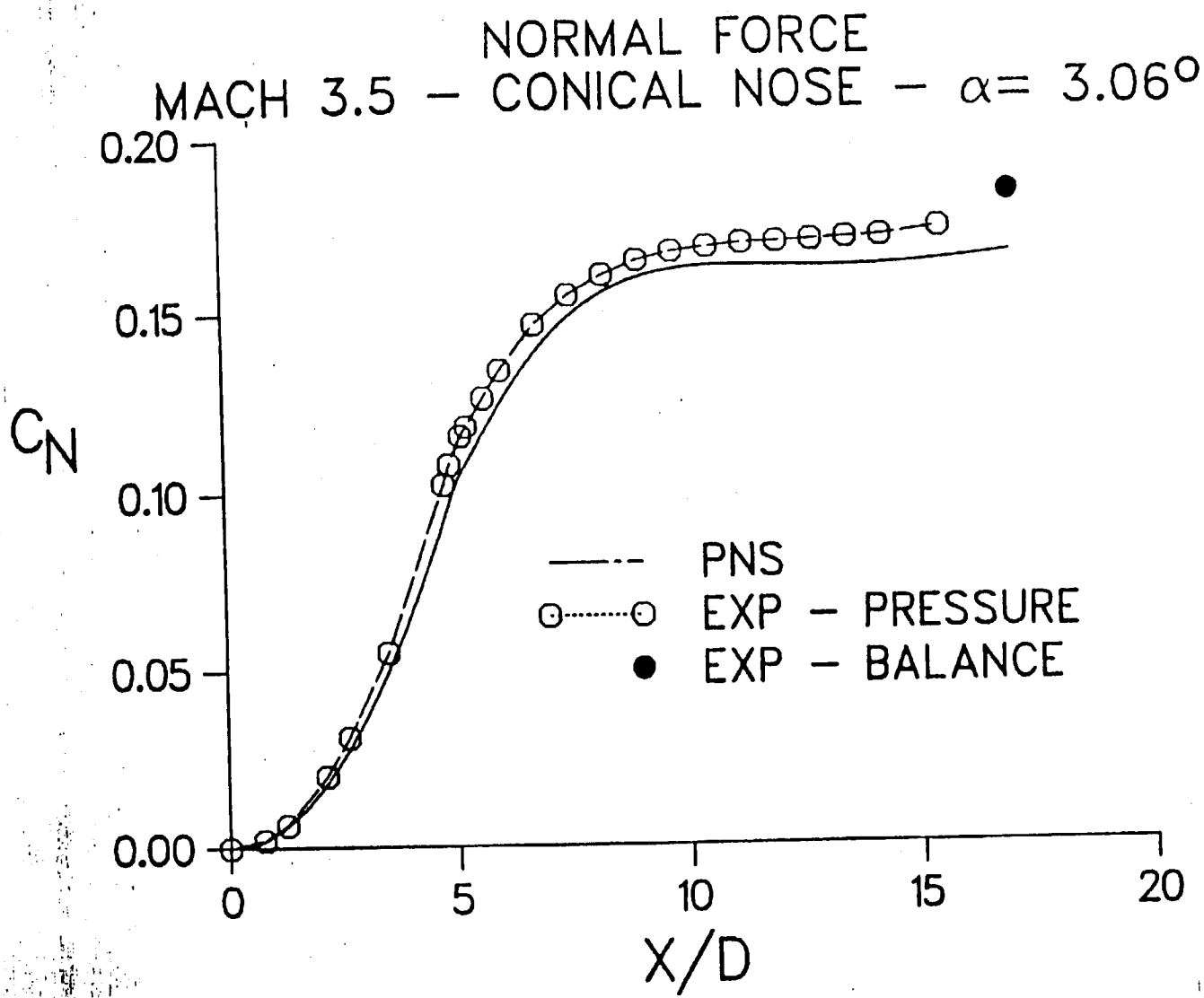
NYU CONFIGURATION – MACH 6.3 – $\alpha = 0.^{\circ}$



CHORDWISE HEAT FLUX DISTRIBUTION – SECTION 3

NYU CONFIGURATION – MACH 6.3 – $\alpha = 0.°$





ORIGINAL PAGE IS
OF POOR QUALITY

AVAILABILITY OF EXPERIMENTAL DATA

($0° < \alpha < 4°$)

Configuration	Mach Number	Velocity Profiles	Surface Pressure	Outer Pressure	Wake/Base Measurements	C_D	C_N or C_{N_α}	C_M or C_{M_α}	C_{ℓ_p}	$(C_{M_q} + C_{M_{\dot{\alpha}}})$	Magnus
Non Spinning Bodies (No Fins)	0.4-1.2	7,12,9,11	1,2,6,8, 9,11,21		8	8	2	2			
	1.2-3.0		1,2,12*, 3,4		19a,19b		2	2			
	> 3.0	13,14,19c	1,2,3,4, 12*,14,19		10,19a						
Spinning Bodies (No Fins)	0.4-1.2	7									
	1.2-3.0										
	> 3.0	13,14	14			5	5	5			5
Long Rod Penetrators (No Spin - One Fin Set	0.4-1.2					17,19	17,19	17,19			
	1.2-3.0					17,19	17,19	17,19			
	> 3.0		15*			17,19	17,19	17,19			
Guided Projectiles (w/2 Sets of Fins No Spin)	0.4-1.2					16	16	16	16	16	
	1.2-3.0					16	16	16	16	16	
	> 3.0										

*Indicates measurement on the fin surface only
**Indicates measurement on the fin surface only

AVAILABILITY OF EXPERIMENTAL DATA

($4° < \alpha < 10°$)

Configuration	Mach Number	Velocity Profiles	Surface Pressure	Outer Pressure	Wake/Base Measurements	C_D	C_N or C_{N_α}	C_M or C_{M_α}	C_{ℓ_p}	$(C_{M_q} + C_{M_{\dot{\alpha}}})$	Magnus
Non Spinning Bodies (No Fins)	0.4-1.2		6,8		8	8					
	1.2-3.0		3,4								
	> 3.0	13	3,4								
Spinning Bodies (No Fins)	0.4-1.2										
	1.2-3.0										
	> 3.0	13					5	5			5
Long Rod Penetrators (No Spin - One Fin Set	0.4-1.2					17,19	17,19	17,19			
	1.2-3.0					17,19	17,19	17,19			
	> 3.0		15*			17,19	17,19	17,19			
Guided Projectiles (w/2 Sets of Fins No Spin)	0.4-1.2					16	16	16		16	
	1.2-3.0					16	16	16		16	
	> 3.0										

*Indicates measurement on the fin surface only

AVAILABILITY OF EXPERIMENTAL DATA

($\alpha > 10°$)

Configuration	Mach Number	Velocity Profiles	Surface Pressure	Outer Pressure	Wake/Base Measurements	C_D	C_N or C_{N_α}	C_M or C_{M_α}	C_{ℓ_p}	$(C_{M_q} + C_{M_{\dot{\alpha}}})$	Magnus
Non Spinning Bodies (No Fins)	0.4-1.2										
	1.2-3.0	18					5	5			
	> 3.0						5	5			
Spinning Bodies (No Fins)	0.4-1.2										
	1.2-3.0						5	5			5
	> 3.0						5	5			5
Long Rod Penetrators (No Spin - One Fin Set	0.4-1.2					19	19	19			
	1.2-3.0					19	19	19			
	> 3.0		15*			19	19	19			
Guided Projectiles (w/2 Sets of Fins No Spin)	0.4-1.2					16	16	16		16	
	1.2-3.0					16	16	16		16	
	> 3.0										

*Indicates measurement on the fin surface only

COMPUTATION ALREADY PERFORMED

Configuration	M \ α	B.L. 0-4	B.L. 4-10	B.L. > 10	Euler 0-4	Euler 4-10	Euler > 10	PNS 0-4	PNS 4-10	PNS > 10	UNS 0-4	UNS 4-10	UNS >10
Non Spinning Bodies (No Fins)	0.4-1.2										21,26,29, 30,32,35, 37,38		
	1.2-3.0										24,31,33		
	> 3.0							25	27				
Spinning Bodies (No Fins)	0.4-1.2										34,36		
	1.2-3.0	41**			4,41**								
	> 3.0	40**			4,40**			20,25, 28*,42	20,27,42		28*		
Long Rod Penetrators (No Spin - One Fin Set	0.4-1.2										26		
	1.2-3.0												
	> 3.0				25			25,27					
Guided Projectiles (w/2 Sets of Fins No Spin)	0.4-1.2												
	1.2-3.0												
	> 3.0												

*Indicates Combined PNS - UNS Solutions
**Indicates Combined BL & Euler Solutions

ISSUES

- DUE TO LACK OF GOOD DATA, CODES ARE BEING USED AS BENCHMARKS
- EXPERIMENTAL DATA NEEDS TO BE VERIFIED TO INSURE QUALITY
- APPLIED CFD IS SPECIALIZED --> SMALL OR NON EXISTING DATA BASE
- EMPHASIS ON APPLYING CFD TO ACTUAL CONFIGURATIONS AND CONDITIONS LIMITS VERIFICATION EFFORTS

I - EXPERIMENTAL DATA ALREADY AVAILABLE AND COMPUTATIONS ALREADY DONE

A. Experimental Data Available

1. Kayser, L.D., "Surface Pressure Measurements on a Projectile Shape at Mach 0.908," US Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, ARBRL-MR-03079, February 1981. (AD A098589)

   - Gives windward and leeward surface pressures on SOCBT, SOC bodies at M = .908 and α = 0°, 2.5°, 5°.

2. Kayser, L.D. and Sturek, W.B., "Aerodynamic Performance of Projectiles with Axisymmetric and Non-Axisymmetric Boattails," US Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, ARBRL-MR-03022, May 1981. (AD 86091)

   - Gives surface pressures on triangular boattails at M = .91, 1.75, 2.0 and 3.0 for α = 2.5°.

3. Sturek, W.B. and Reba, J., "Measurements of Wall Static Pressure on a Yawed Tangent-Ogive-Cylinder Model," US Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, ARBRL-MR-2699, November 1976. (AD A033275)

   - Gives axial and circumferential static pressure measurements at M = 2, 3, 4 and α = 0° - 10°.

4. Reklis, R.P. and Sturek, W.B., "Surface Pressure Measurements on Slender Bodies at Angle of Attack in Supersonic Flow," US Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, ARBRL-MR-02876, November 1978. (AD A064097)

   - Gives axial static surface pressure at M = 2, 3, 4, α = 0°, 1°, 2°, 4°, 6°, 10°, for four typical projectile configurations at ϕ = 0° → 180°, $\Delta\phi$ = 10°.

5. Nietubicz, C.J. and Opalka, K.O., "Supersonic Wind Tunnel Measurements of Static and Magnus Aerodynamic Coefficients For Projectile Shapes with Tangent and Secant Ogive Noses," US Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, ARBRL-MR-02991, February 1980. (AD A083297)

   - Gives side force and Magnus moment at M = 2, 3, 4 for α = 4° - 12°, PD/V = 0 - .4.

6. Kayser, L.D. and Whiten F., "Surface Pressure Measurements on a Boattailed Projectile Shape at Transonic Speeds," US Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, ARBRL-MR-03161, March 1982. (AD A113520)

   - Gives wall static pressure measurements at M = .91, .94, .96, .98, 1.10, 1.2 for α = 0° - 10°, at $\Delta\phi$ = 22.5° increments.

7. Nietubicz, C.J. and Nusca, M., "Transonic LDV Measurements for Blunted Bodies of Revolution," unpublished data, US Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, Memorandum Report to appear in 1986.

- Provides velocity profiles at M = .91 and α = 0°, 4°, spin = 0, 20000 rpm for a SOCBT configuration.

8. Kayser, L.D., "Base Pressure Measurements on a Projectile Shape at Mach Numbers from 0.91 to 1.20," US Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, ARBRL-MR-03353, April 1984. (AD A141341)

- Gives surface and base pressure measurements at M = .91, .94, .96, .98, 1.1, 1.2, for α = 0° - 10°, $\Delta\phi$ = 22.5° for SOC and SOCBT configurations.

9. Danberg, J.E. and Tschirschnitz, R.H., "Measurements on a Projectile with an Asymmetric Afterbody at Transonic Speeds," AIAA Paper No. 83-0545, January 1983.

- Gives pressure measurements and velocity profiles at M =.94, .97 and α = 0°, 4° for nonspinning projectile with triangular afterbody.

10. Kayser, L.D. and Danberg, J.E., "Experimental Study of Separation from the Base of a Cone at Supersonic Speeds," AIAA Journal, Vol. 12, No. 11, November 1974, pp. 1607-1609.

- Gives single profile for the base pressure of a cone with a sting at M_∞ = 3.0 and α = 0°.

11. Reklis, R.P., Danberg, J.E. and Inger, G.R., "Boundary Layer Flows on Transonic Projectiles," AIAA Paper No. 79-1551, July 1979.

- Gives pressure and velocity profiles for projectile with conical boattail at M = .80, .94, .97 and α = 0°, 2°.

12. Danberg, J.E. and Palko, K.L., "Measurement of Surface Pressures Caused by a Projectile Rotating Band at Supersonic Speeds," US Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, ARBRL Report under preparation, April 1986.

- Gives pressure measurements at and near a rectangular rotating band of a projectile at M = 2.5, 3.0, 3.5 and α = 0°

13. Kayser, L.D. and Sturek, W.B., "Experimental Measurements in the Turbulent Boundary Layer of a Yawed Spinning Ogive-Cylinder Body of Revolution at Mach 3.0 - Part II: Data Tabulation," US Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, ARBRL-MR-02813, March 1978. (AD A053458)

- Gives velocity, temperature, density turbulent boundary layer profiles at M = 3, for α = 0°, 2.1°, 4.2°, 5.3°, 6.3°, spin = 0 and 20000 rpm.

14. Kayser, L.D. and Sturek, W.B., "Turbulent Boundary Layer Measurements on the Boattail Section of a Yawed, Spinning Projectile Shape at Mach 3.0," US Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, ARBRL-MR-02880, November 1978. (AD A065355)

- Gives surface pressure measurements at M = 3. for SOC and SOCBT configurations at $\alpha = 0°, 2°$. Also gives velocity profiles at M = 3, $\alpha = 2°, 4.2°$, $\omega = 2 \times 10^4$ rpm.

B. Relevant Non-BRL Experimental Data Available

Fin Data for KE Projectile

15. Agnone, A.M. and Zakkay, V. and Weinacht, P., "Hypersonic Flow Over a Six Finned Configuration," AIAA Paper No. 85-0453, January 1985.

- Provides fin surface pressure and heat flux measurements for a six-fin projectile at $M = 6.3$, $\alpha = 0°, 5°, 10°$ and $\phi = 0°, 15°, 30°$.

NOTE: The principal author indicated that these results are only preliminary, however, the final results are expected to be reported in August 1986.

The Aerodynamics of Guided Projectiles

16. Appich, W.H. and Wittmeyer, R.E., "Summer 1978 - Aerodynamic Simulation Model Update: Full Scale Model Data XM-939," Martin Marietta Corporation, Report No. ANA 960000-010, September 1978.

- Provides wind tunnel force and moment data for the Copperhead projectile in the Mach range $M = 0.5 - 1.8$, $\alpha = 0° - 20°$, $\delta = -20°$ to $20°$

Force Measurements for Large L/D Projectiles with Conical Flare

17. Spring, D.J., "The Static Stability Characteristics of Several Cone-Cylinder-Flare-Cylinder Configurations at Mach Numbers 0.4 to 4.5," US Army Missile Command, Redstone Arsenal Report, RF-TR-63-14, June 1963.

- Provides force and moment measurements for large L/D (8.6 - 15.3), and small flare semi-cone angles (0°, 4°, 6°, 8°), for Mach numbers 0.4 - 4.5, $\alpha = -6°$ to $+6°$.

Large Angle of Attack Body-Vortices Measurements for Large L/D Bodies

18. Oberkampf, W.L. and Bartel, T.J., "Symmetric body Vortex Wake Characteristics in Supersonic Flow," AIAA Journal, Vol. 18, No. 11, November 1980, pp. 1289-1297.

- Provides center of wakes (body vortices) for a projectile at $M = 1.95$, 2.0, 3.01 at $\alpha = 10°, 15°, 20°, 25°$.

NOTE: Data tabulation provides u,v,w velocity components throughout the flowfield. Data are available from author.

Body-Wing-Tail Force Data

19. Gomillion, G.R., "A Compilation of Static Stability and Fin Loads Data for Slender Body Missile Models with and without Tail Fins and Wings - Vol. 1," AEDC-TR-75-125 and AFATL-TR-76-23, March 1976.

- Provides force measurements for body alone, body-wing, and body-wing-tail configurations in the Mach range of 0.2 to 4.63 and α from -6° to +60°.

Base Bleed

19a. Agrell, J. and White, R.A., "An Experimental Investigation of Supersonic Axisymmetric Flow Over Boattails Containing a Centered Propulsive Jet," FAA Technical Note AU-913, 1974.

- Provides base and boattail pressure data in the Mach range M = 2.01, 3.27, α = 0° with M_j = 2.5 .

19b. Petrie, H.L. and Walker B.J., "Comparison of Experiment and Computation for a Missile Base Region Flowfield with a Centered Propulsive Jet," AIAA Paper No. 85-1618, July 1985.

- Provides base pressure and wake velocity vectors for a single case with M_∞ = 1.4, M_j = 2.7, α = 0°.

Aerodynamics of Sharp and Blunted Bodies

19c. Gray, W.K. and Dolling, D.S., "An Experimental Investigation of Tip Bluntness Effects on the Turbulent Compressible Boundary Layer on Axisymmetric Body," Princeton University Report, Mechanical and Aerospace Engineering Department, Princeton, NJ 08544, May 1981.

- Provides boundary layer pressure profiles and longitudinal surface pressures at M = 2.94 and α = 0°, 2-9° for tangent ogive-cylinder configuration with six different nose bluntness.

C. Computations Already Performed

20. Sturek, W.B. and Schiff, L.B., "Computations of the Magnus Effect for Slender Bodies in Supersonic Flow," US Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, ARBRL-TR-02384, December 1981. (AD A110016)

    - PNS calculations for spinning cone, ogive cylinder, for $\alpha < 6°$, $M = 3$, $\Omega = 333 - 500$ RPS.

21. Nietubicz, C.J., Danberg, J.E. and Inger, G.R., "A Theoretical and Experimental Investigation of a Transonic Projectile Flow Field," US Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, ARBRL-MR-03291, July 1983. (AD A131938)

    - N-S calculations, at $\alpha = 0°$, $M = .97$ for a SOCBT. Also provides experimental data, at the same conditions, for surface pressures and velocity profiles.

22. Sturek, W.B., Kayser, L.D., Mylin, D.C. and Hudgins, H., "Computational Modeling of Aerodynamic Heating for XM797 Nose Cap Configurations," US Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, ARBRL-TR-02523, September 1983. (AD A133684)

    - Unsteady temperature response using shape-change code.

23. Weinacht, P., Sturek, W.B. and Wooden, P.A., "Computational Study of Inbore and Inflight Heating for the 105mm, M774 Projectile Modified Swept Fin," US Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, ARBRL-MR-03377, August 1984. (AD A146568)

    - 2-D unsteady heat transfer computation for $V_\infty = 5000$ ft/sec for 2.0 seconds.

24. Sahu, J. and Nietubicz, C.J., "Numerical Computation of Base Flow for a Missile in the Presence of a Centered Jet," ARBRL-MR-3397, October 1984. (AD A148784)

    - N-S calculations (axisymmetric) at $M = 1.343$, $\alpha = 0°$, jet on and off.

25. Weinacht, P. Guidos, B.J., Kayser, L.D. and Sturek, W.B., "PNS Computations for Spinning and Fin-Stabilized Projectiles at Supersonic Velocities," US Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, ARBRL-MR-3464, September 1985. (AD A160393)

    - PNS computations, 3D, at $M = 3 - 5$, $\alpha = 2°$ for finned projectile and SOCBT, at $PD/V = 0, 0.19$.

26. Sahu, J. and Nietubicz, C.J., "Numerical Flow Field Calculations for a Missile Configuration at $M = .6$," US Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, ARBRL-MR-3491, January 1986.

    - Thin layer N-S (axisymmetric) computations at $M = .6$, $\alpha = 0°$.

458 Q-6

27. Weinacht, P., Guidos, B.J., Sturek, W.B. and Hodes, B.A., "PNS Computations for Spinning Shell at Moderate Angles of Attack and for Long L/D Finned Projectiles," AIAA Paper No. 85-0273, January 1985.

- 3D, PNS computations for a spinning SOCBT ($M = 3.$, $\alpha = 6.3°$, PD/V = 0.0, 0.19) and nonspinning long L/D, finned projectile ($M = 4.$, $\alpha = 2°$, L/D = 12.5, 6-fins)

28. Sturek, W.B., Guidos, B.J. and Nietubicz, C.J., "Computational Study of Nose Bluntness Effects for Spinning Shell at Supersonic Speeds," Journal of Spacecraft and Rockets, Vol. 21, No. 1, January-February 1984, pp. 16-20. (Also AIAA Paper 82-1341)

- 3D, thin layer N-S calculations for blunt and sharp nose, spinning, SOCBT projectile body. PNS calculations are coupled to blunt nose computations to yield solutions at $M = 3.$, $\alpha = 2°$, PD/V = .19 .

29. Sahu, J. and Nietubicz, C.J., "Numerical Computation of Base Flow for a Projectile at Transonic Speeds," AIAA Paper No. 82-1358, August 1982.

- Axisymmetric N-S computations for a nonspinning projectile at $\alpha = 0°$ and for Mach numbers 0.9, 0.96, 0.98, 1.1, 1.2 .

30. Sahu, J. and Danberg, J.E., "Navier-Stokes Computations of Axisymmetric Transonic Flows with a Two-Equation Model of Turbulence," AIAA Paper No. 85-0373, January 1985.

- Axisymmetric N-S computations for a nonspinning projectile at $\alpha = 0°$, M = .94 and for a projectile with a bump (rotating band) at $M = .875$, $\alpha = 0°$.

31. Sahu, J. "Computations of Supersonic Flow Over a Missile Afterbody Containing an Exhaust Jet," AIAA Paper No. 85-1815, August 1985.

- Axisymmetric N-S computations for boattailed projectile at $M_\infty = 2.0$, $M_{jet} = 2.5$ and nozzle static pressure ratios of 1.0, 3.0 and 9.0, $\alpha = 0°$.

32. Sahu, J., Nietubicz, C.J. and Steger, J.L., "Navier-Stokes Computations of Projectile Base Flow with and without Mass Injection," AIAA Journal, Vol. 23, No. 9, September 1985, pp. 1348-1355.

- Axisymmetric N-S computations for projectile with mass injection at M = 0.9, 0.98, 1.1, 1.2, $\alpha = 0°$, for injection parameters of I = 0.0, 0.13 .

33. Sahu, J., "Supersonic Flow Over Cylindrical Afterbodies with Base Bleed," AIAA Paper No. 86-0487, January 1986.

- Axisymmetric N-S computations for projectiles with square boattail, at $\alpha = 0°$, M = 1.7, 2.5, with injection parameter I = .01, .02 .

34. Nietubicz, C.J., Pulliam, T.H. and Steger, J.L., "Numerical Solution of the Azimuthal Invariant Thin Layer Navier-Stokes Equations," AIAA Journal, Vol. 18, No. 12, December 1980, pp. 1411-1412.

- Axisymmetric N-S computations for a spinning projectile at M = .95, PD/V = 0.11, α = 0°.

35. Nietubicz, C.J., "Navier-Stokes Computations for Conventional and Hollow Projectile Shapes at Transonic Velocities," AIAA Paper No. 81-1262, June 1981. (Also as ARBRL-MR-03184) (AD A116866)

- 3D N-S computations for a SOCBT configuration at M = .8, .94, .96, 1.1 for α = 0°, 2°; and for ring-airfoil projectile at M = .4, .7, .8, .9 and α = 0° .

36. Nietubicz, C.J., Sturek, W.B. and Heavey, K.R., "Computations of Projectile Magnus Effect at Transonic Velocities," AIAA Journal, Vol. 23, No. 7, July 1985, pp. 998-1004.

-3D N-S computations for a SOCBT configuration, at M = .91, α =2°, PD/V = 0.39 .

37. Nietubicz, C.J. and Danberg, J.E., "Theoretical and Experimental Investigation of a Transonic Projectile Flow Field," AIAA Journal, Vol. 22, No. 1, January 1984, pp. 35-41.

- Axisymmetric N-S computations at M = .94, .97 for a SOCBT configuration, α = 0°.

38. Nietubicz, C.J., Mylin, D.C., Sahu, J. and Lafarge, R., "Aerodynamic Coefficient Predictions for a Projectile Configuration at Transonic Speeds," AIAA Paper No. 84-0326, January 1984.

- 3D N-S computations for the 549 projectile at M = .9, .95, .98 and α = 2° .

39. Sturek, W.B., Kayser, L.D. and Mylin, D.C., "Boundary-Layer Trip Effectiveness and Computations for Aerodynamic Heating for XM797 Nose-Tip Configuration," US Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, ARBRL-MR-03262, April 1983 (AD A127454)

- Gives temperature history for nose tip configurations at Mach 4.4 .

40. Sturek, W.B. et al, "Computations of Magnus Effects for a Yawed Spinning Body of Revolution," AIAA Journal, Vol. 16, No. 7, July 1978, pp. 687-692.

- Combined 3D boundary layer and inviscid calculation for a SOC body at M = 3, α = 2°, 4° at spin rate of 20,000-30,000 rpm.

41. Sturek, W.B., Mylin, D.C. and Bush, C.C., "Computational Parametric Study of the Aerodynamics of Spinning Slender Bodies at Supersonic Speeds," AIAA Paper No. 80-1586R.

- Combined 3D boundary layer and inviscid calculation to yield the flow field for SOC and cone-cylinder at M = 1.7 to 5.0, α = 0°, 1°; PD/V = .19 .

42. Sturek, W.B. and Schiff, L.B., "Numerical Simulation of Steady Supersonic Flow over Spinning Bodies of Revolution," AIAA Journal, Vol. 20, No. 12, December 1982, pp. 1724-1731.

- PNS computation for ogive-cylinder with and without boattail, at M = 3.0, α = 2°, 6.3° and 10.4°, spin = 20,000 rpm .

VALIDATION OF CFD FOR AIRCRAFT DESIGN

A BOEING VIEW

IRWIN E. VAS

14 JULY 1987

SUPPORTED BY
C. FORESTER, H. YOSHIHARA – BMAC
T. NARK, S. BIRCH – BAC
R. BENGELINK, P. RUBBERT, J. LEE – BCAC

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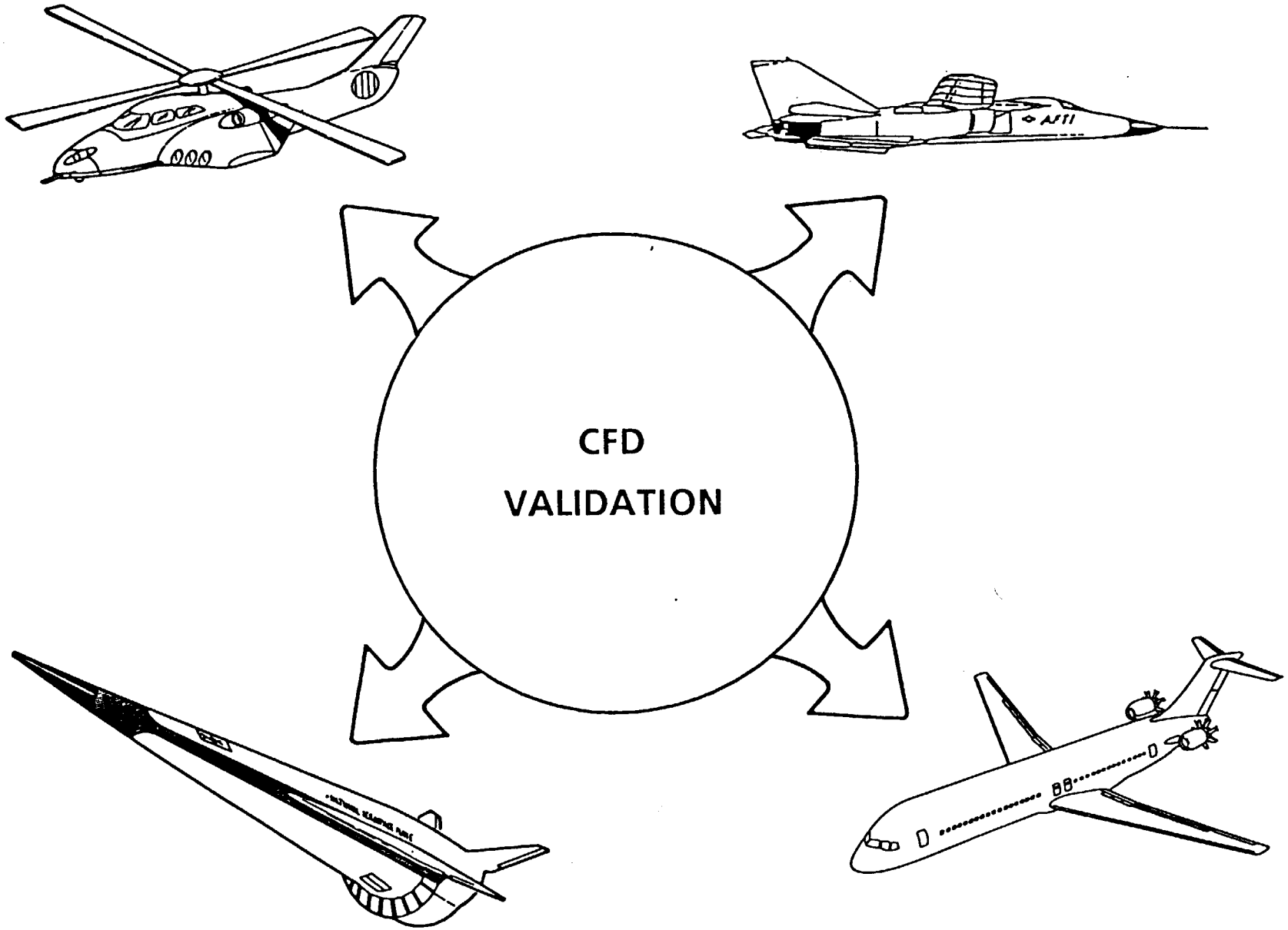
CFD VALIDATION FOR ADVANCED SYSTEMS



OBJECTIVES AND GOALS FOR CFD

OBJECTIVES	GOAL STATUS
DETERMINE FORCES AND MOMENTS ACCURATELY	THIS GOAL IS PREMATURE
DETERMINE INCREMENTAL EFFECTS DUE TO CONFIGURATION PERTURBATIONS	POSSIBLE, BUT WITH UNACCEPTABLE ERROR BAND
DETECT UNDESIRABLE FLOW FEATURES (UNSWEPT SHOCKS, SEPARATION, ETC.) AND ELIMINATE THEM	PROBABLY REALISTIC

CFD VALIDATION – A DEFINITION

- CORRECT PHYSICAL MODELING OF TURBULENCE, TRANSITION, SEPARATION, CHEMISTRY, ETC. – CHECKED BY BENCHMARK EXPERIMENTS
- CORRECT APPLICATION OF CERTIFIED CFD CODE TO GEOMETRY
- TEST GEOMETRY – CERTIFY EXPERIMENTAL ACCURACY
- COMPARE CERTIFIED CFD AND CERTIFIED EXPERIMENT OF GEOMETRY

ADVANCED SYSTEMS

SUBSONIC

- COMMERCIAL TRANSPORT
- TRANSONIC TRANSPORT
- ROTOR CRAFT
- SHORT TO/VERTICAL LAND
- HIGH ALTITUDE, LONG ENDURANCE
- REMOTELY PILOTED VEHICLE

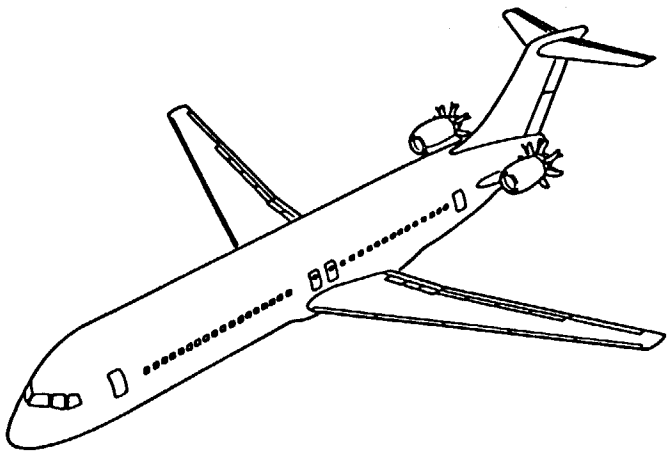
SUPERSONIC

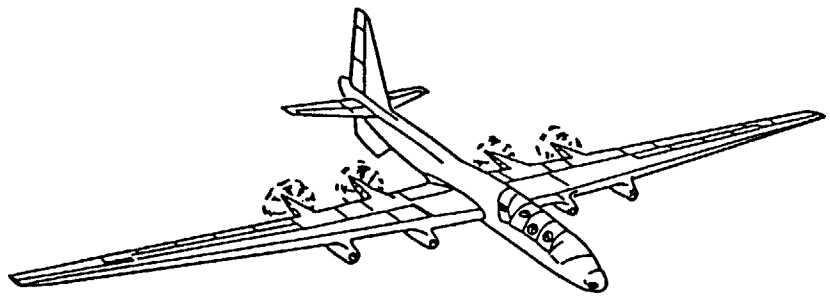
- SUPERSONIC TRANSPORT
- SUPERSONIC STRIKE VEHICLE
- RECONNAISSANCE
- ADVANCED TACTICAL FIGHTER

HYPERSONIC

- HYPERSONIC TRANSPORT
- NATIONAL AEROSPACE PLANE
- HYPERVELOCITY INTERCEPTOR
- STRATEGIC STRIKE VEHICLE
- HYPERSONIC MISSILE
- HYPERVELOCITY GLIDE VEHICLE

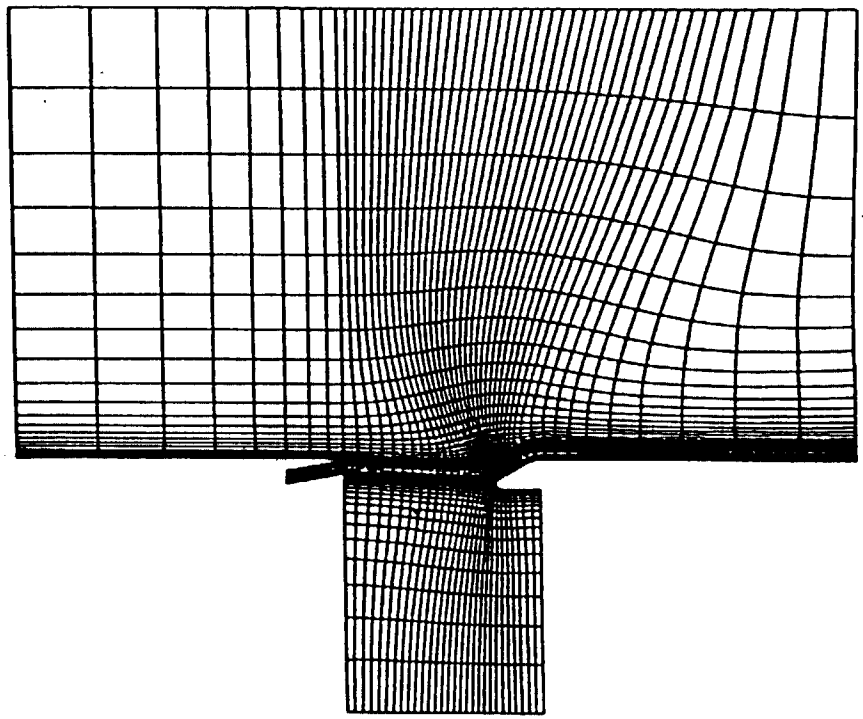
CRITICAL ISSUES
SUBSONIC EXTERNAL

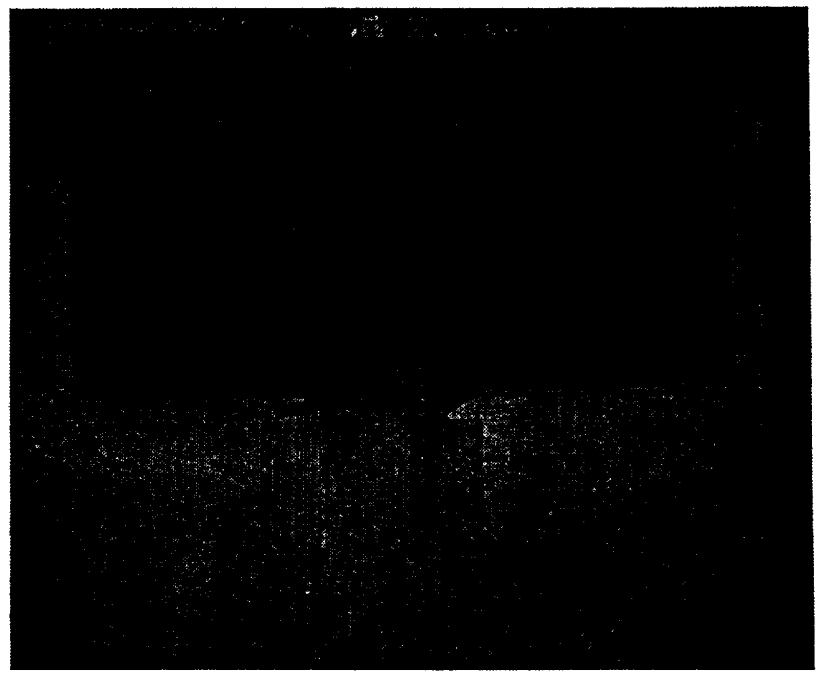




- NATURAL LAMINAR FLOW
- BOUNDARY LAYER CONTROL
- HIGH- α AERODYNAMICS
- VORTEX FLOWS
- CAVITY FLOWS
- REDUCED TURBULENT DRAG
- OPTIMIZE LIFT / DRAG MULTI-ELEMENT HIGH LIFT
- TRANSITION DETERMINATION

VERIFICATION – SUBSONIC, EXTERNAL
CAVITY FLOW



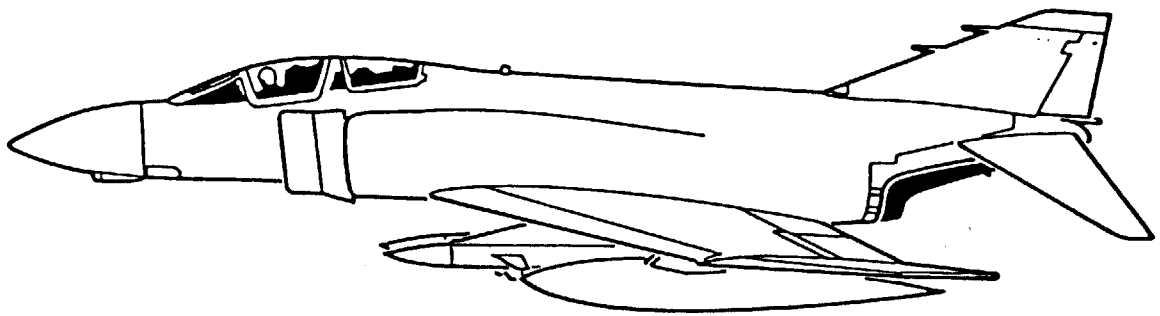


$M_\infty = 0.65$

$P_o = 1$ atm

$T_o = 300K$

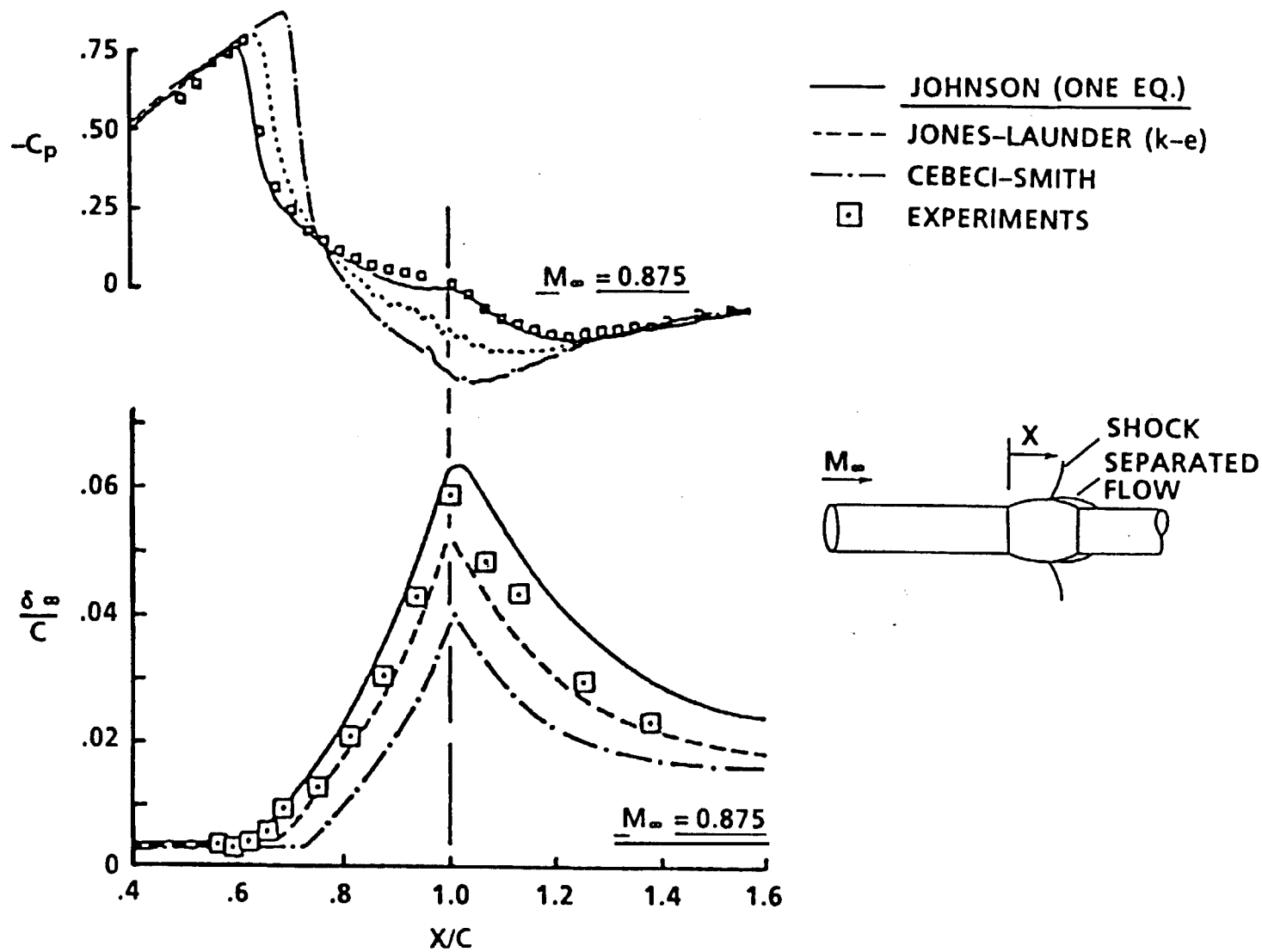
CRITICAL ISSUES
TRANSONIC



- MINIMIZE DRAG RISE $0.8 < M < 1.3$
- VORTEX FLOWS AT HIGH α
- DIRECT SIMULATION OF VORTEX GENERATOR PROPERTIES
- MODELING OF TRANSONIC SEPARATED FLOW TURBULENCE
- CAVITY FLOWS
- SHOCK BOUNDARY LAYER INTERACTION

TRANSONIC SEPARATED FLOWS

EFFECT OF TURBULENCE MODELING



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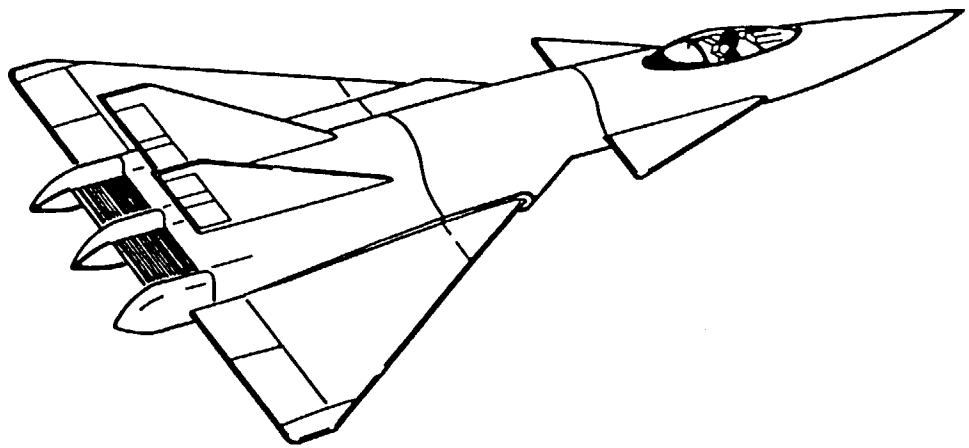
CRITICAL ISSUES – SUPERSONIC, EXTERNAL

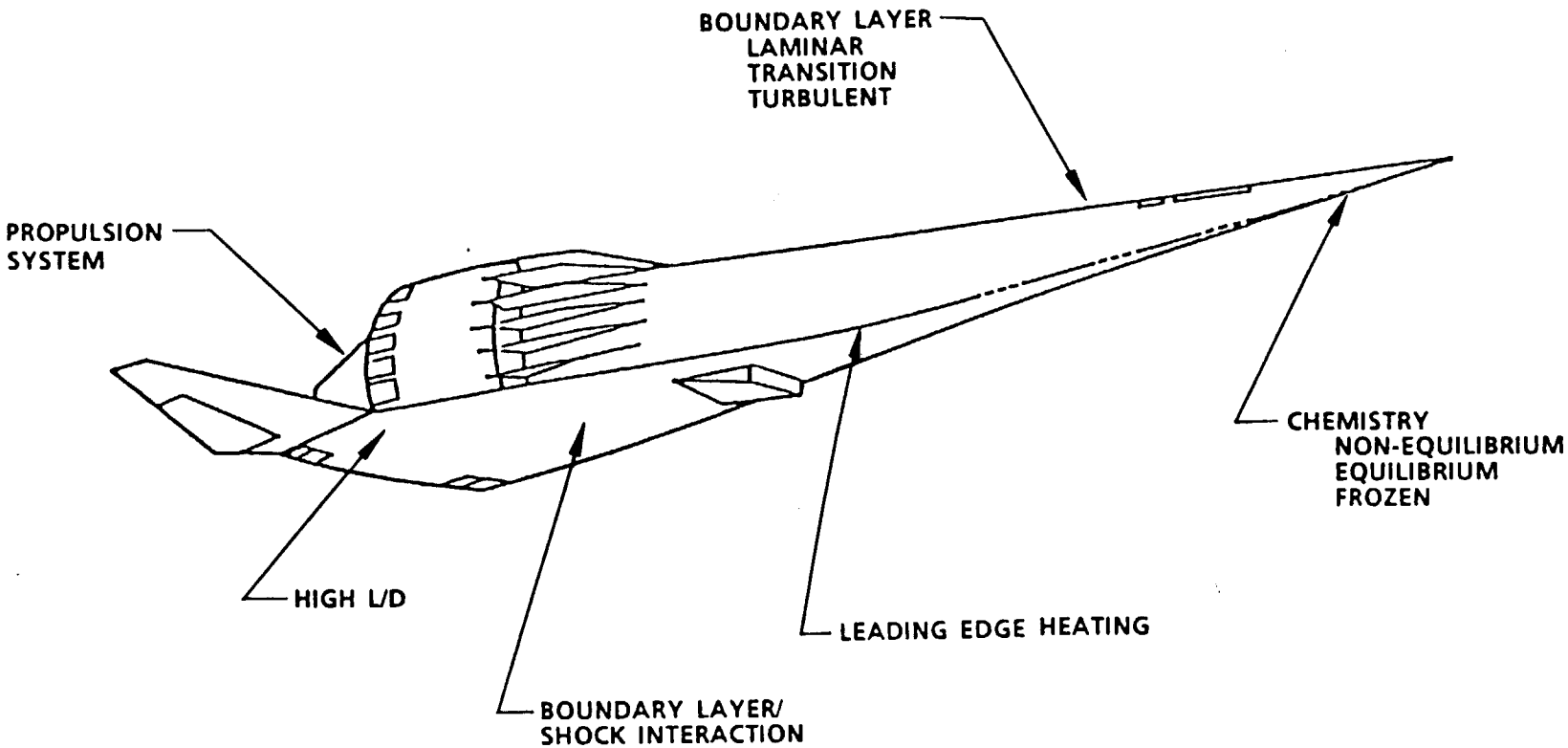


- AERODYNAMIC HEATING, LAMINAR, TURBULENT, ATTACHED AND SEPARATED FLOWS
- VORTEX DYNAMICS FOR HIGH α CONDITION
- SHOCK / BOUNDARY LAYER INTERACTION
- SHOCK / SHEAR LAYER INTERACTION
- MULTI-ELEMENT HIGH LIFT AERODYNAMIC DEVICES
- HIGH MANEUVERABILITY
- CAVITY FLOWS

CRITICAL ISSUES – SUPERSONIC, INTERNAL

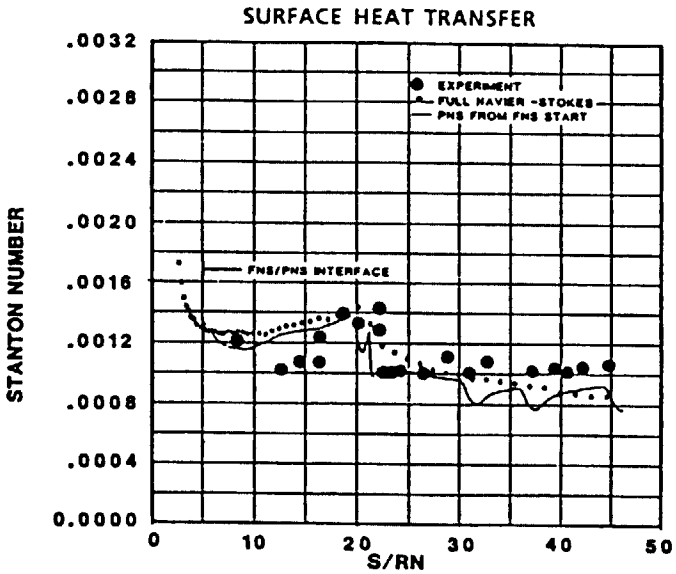
- MULTIPLE SHOCK / VORTEX / BOUNDARY LAYER INTERACTION
- SMALL CENTER LINE OFFSET
- LARGE CENTER LINE OFFSET
- DISTORTION PARAMETERS FOR ENGINE INTAKE
- TOTAL PRESSURE LOSSES

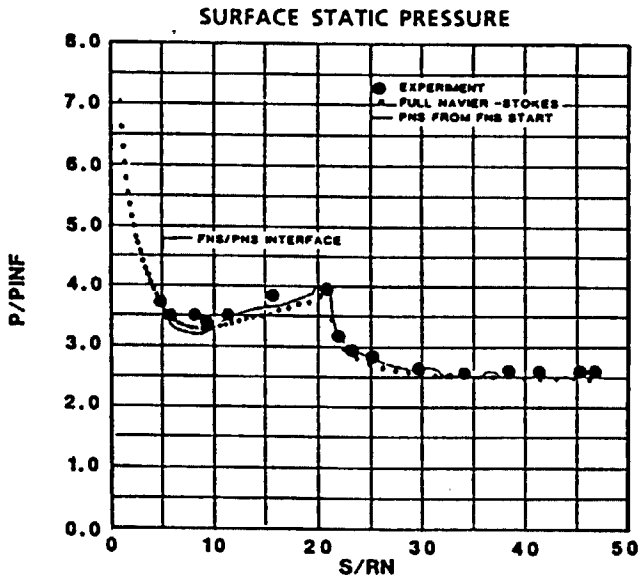
CRITICAL ISSUES – HYPERSONIC EXTERNAL

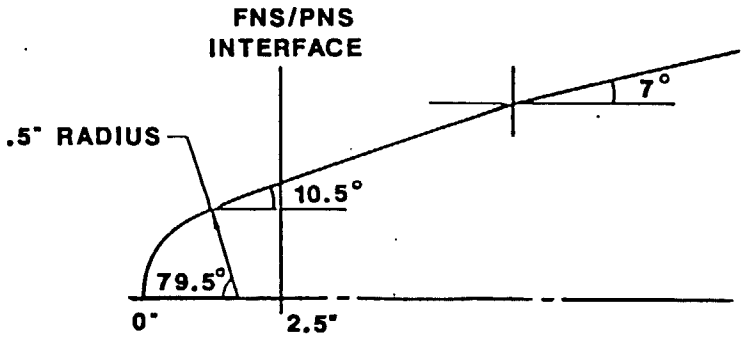


VERIFICATION – HYPERSONIC, EXTERNAL

MACH 8 BICONIC GEOMETRY

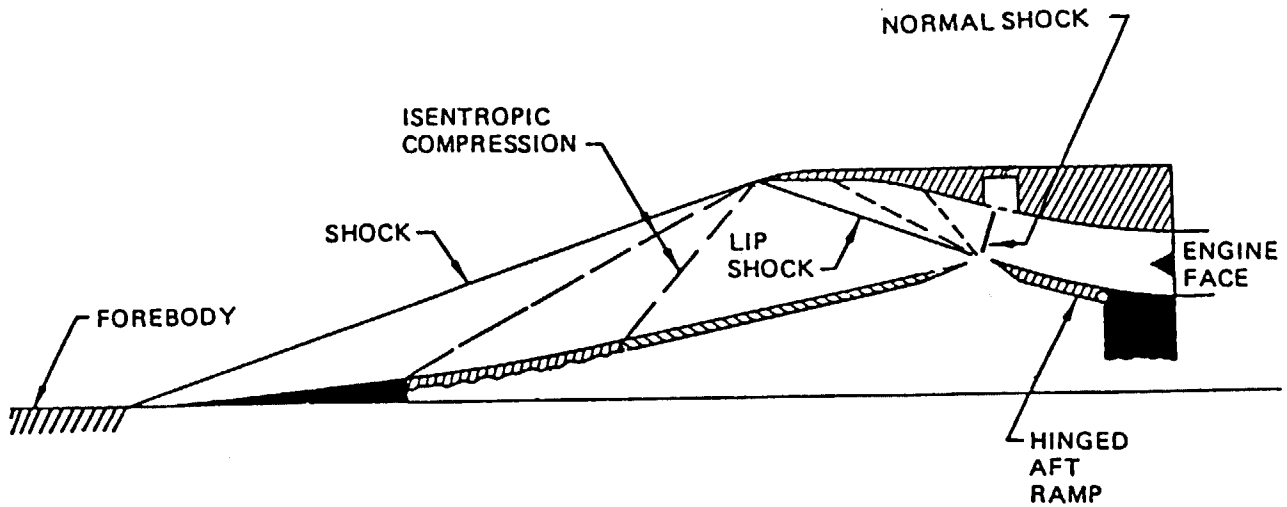






MACH=7.97
REYNOLDS NUMBER=9.23×10^6
TURBULENT FLOW-BALDWIN/LOMAX TURBULENCE MODEL
EQUILIBRIUM AIR ASSUMED
T=99°R,P =12.6 psf

CRITICAL ISSUES – HYPERSONIC, INTERNAL



- MULTIPLE SHOCK / VORTEX / BOUNDARY LAYER INTERACTIONS
- CENTER LINE OFFSET
- EQUILIBRIUM / NON-EQUILIBRIUM CHEMISTRY
- QUICK/SLOW ENERGY RELEASE
- SEPARATED FLOWS

Once upon an Approach to C.F.D.
C.F.D. Kitchen
Peck-Peck
Eye of Newton
Nest of Dissection
Greek
Euler
Boundary Layer
Viscous Flows
Thrust
Wings
Jameson
Line
Navier-Stokes
Seidel
Reserved for Results
Results
Cray Computer
Hyper Link
Research
Eks IBM
Pop
Vax
IRIS

70701-171V

STEPS TO CODE VALIDATION

ELIMINATE NUMERICAL ERRORS

- 2 D EULER CASE (AIRFOILS)
  - ESTABLISH ACCEPTABLE MESH AT LEADING EDGE, SHOCK, TRAILING EDGE
  - ESTABLISH ACCEPTABLE FAR FIELD BOUNDARY LOCATION
  - ESTABLISH ACCEPTABLE ARTIFICIAL VISCOSITY
- 2 D LAMINAR NAVIER–STOKES
  - AS "A"
  - ESTABLISH MESH FOR BOUNDARY LAYER
- 3 D SWEPT WING (EULER, LAMINAR OR TURBULENT N. S. EQS.)
  - ESTABLISH ACCEPTABLE 3 D MESH (SPANWISE AND TIP MESH CONFIGURATION
  - SHOCK CAPTURE FOR SWEPT SHOCKS
- COMPLETE CONFIGURATION (EULER, LAMINAR OR TURBULENT N. S. EQS.)
  - ESTABLISH VIABILITY OF MULTI–BLOCK MESH GENERATION

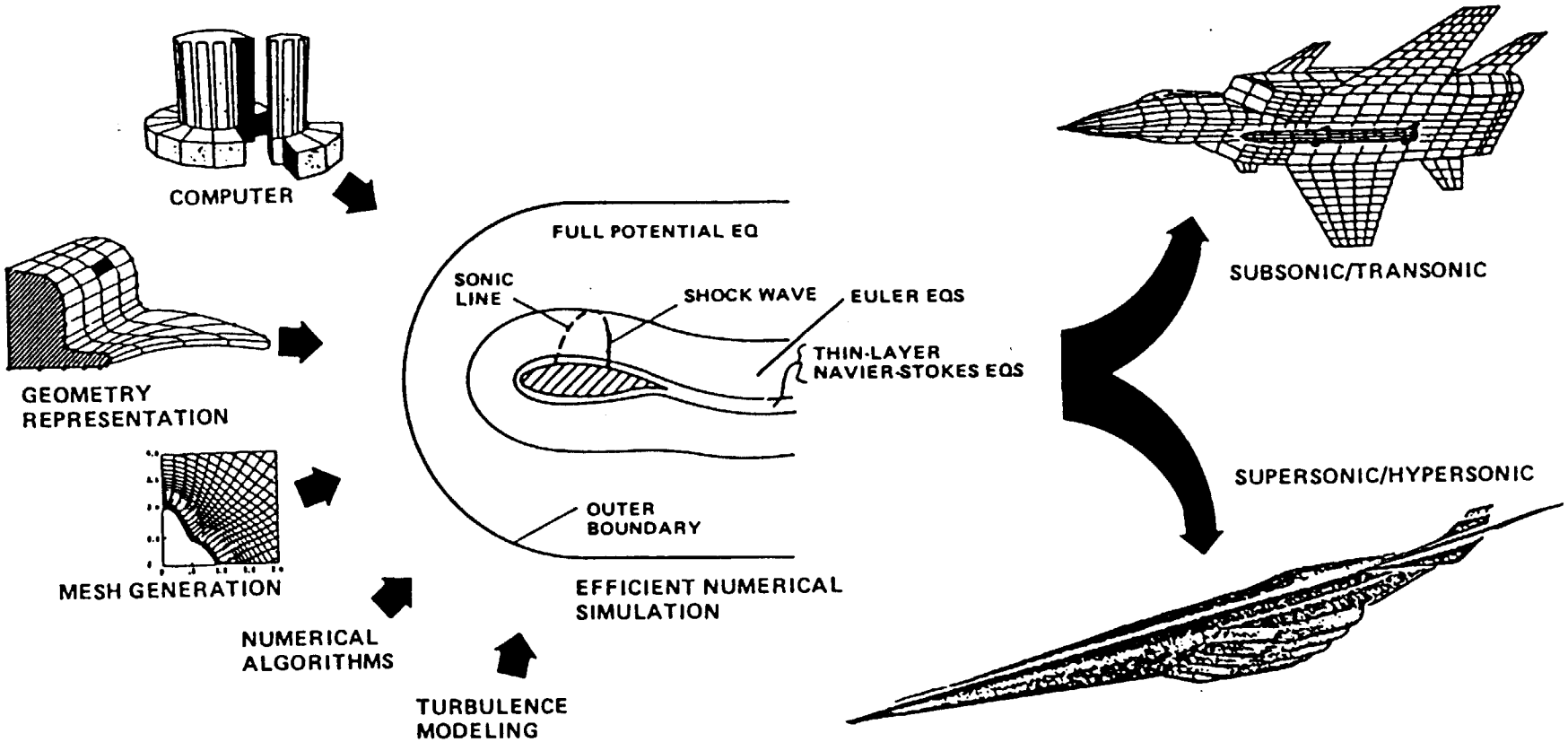
STEPS TO CODE VALIDATION (CONT.)

IDENTIFY FLOW MODELING SHORTCOMINGS (AFTER NUMERICAL ERRORS ELIMINATED)

- TURBULENCE MODELING
  - FOR COMPLEX CASES (SHOCK / BOUNDARY LAYER, CAVITY, VORTEX CORES . . . .)
  - CROSS-FLOW EFFECTS (SWEPT SEPARATIONS, WING, FUSELAGE, . . .)
- TRANSITION MODELING
  - INCOMPRESSIBLE TURBULENCE (3-D CONTAMINATION, BLC DEVICE, . . .)
  - COMPRESSIBLE TURBULENCE (HYPERVELOCITY CASE WITH LOW REYNOLDS NUMBER EFFECTS, . . .)
- DESIGN AND CARRY OUT EXPERIMENTS TO MODEL ABOVE
  - NON-INTRUSIVE
  - USE AFFORDABLE FACILITIES WHEREVER POSSIBLE (UNIVERSITY, COOPERATIVE . . .)

CFD APPROACH

ZONAL MODELING



COORDINATED DEVELOPMENT/ ACQUISITION OF CFD ELEMENTS → CONSTRUCT ZONAL SOLUTION METHODS FOR SPECIFIC APPLICATIONS → **GENERATE DESIGN INFORMATION**

MATHMATICAL FOUNDATION FOR NAVIER–STOKES SIMULATION

$AX = B$ BASIC FORMULATION DISCRETIZATION

$P'AP = U$ MATRIX IDENTITY

$A = P\Lambda P^{-1}$

$\Lambda_i = \lambda_1, \lambda_2, \lambda_3, \ldots$ EIGEN VALUES ALONG DIAGONAL OF U

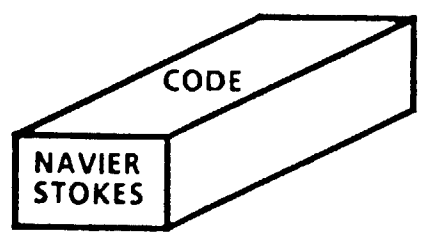
U IS AN UPPER TRIANGULAR MATRIX

$\Downarrow$

NEWTON–LIKE METHODS OF SOLVING THE EQUATIONS

EXAMPLE

ARC3D, PEPSIS, CFL3D



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CFD GENERALIZE TRANSPORT EQUATION

ENCOMPASS ALL PHYSICS OF CONTINUUM

$$\frac{\bar{U}}{t} + \frac{\bar{F}}{x} + \frac{\bar{G}}{y} + \frac{\bar{H}}{z} = S_{(x, y, z)}$$

FOR EXAMPLE

$$\bar{U} = \begin{Bmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ E \\ s_1 \\ s_2 \\ \cdot \\ \cdot \end{Bmatrix}$$

CONTINUITY
x MOMENTUM
y MOMENTUM
z MOMENTUM
ENERGY
SPECIES 1
SPECIES 2
⋮

S INCLUDES

- HEAT OF FORMATION
- HEAT TRANSFER
- MASS INJECTION
- $_1 = {}_1(a, b, c, \ldots)$
- $_2 = {}_2(e, f, g, \ldots)$

TRANSPORT COEFFICIENTS OF HEAT, MASS, MOMENTUM, SPECIES, ETC.

CFD PHYSICAL MODELING

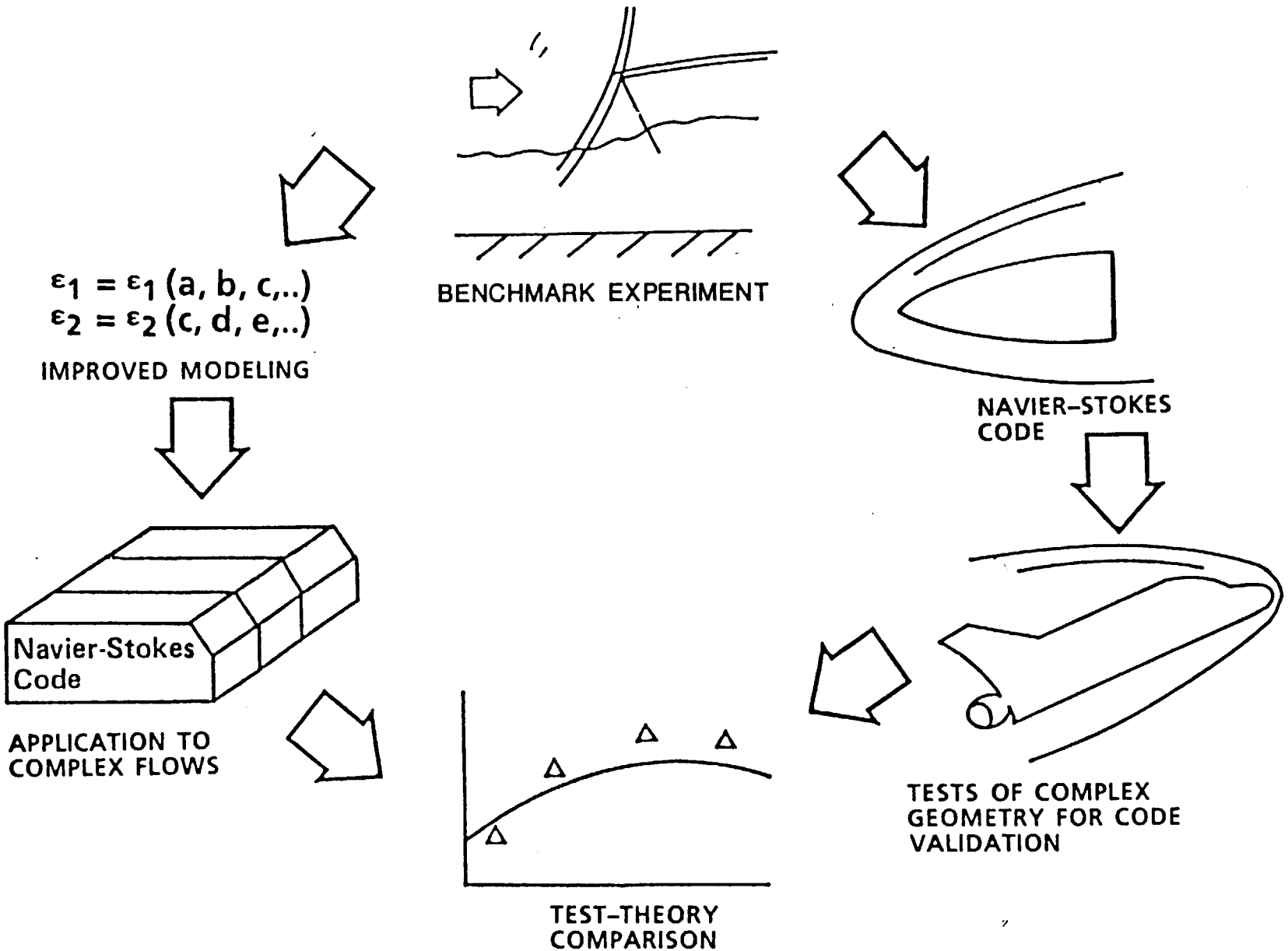
- USE FULL NAVIER-STOKES DIRECT SIMULATION (FNS-DS) OF SEPARATION, TRANSITION AND DEVELOPED TURBULENCE

- CHECK FNS-DS
- BENCH MARK EXPERIMENT

- IMPROVE PHYSICAL MODELING;
  - WITH CERTIFIED DATA BASE
  - WITH FNS-DS

- APPLY CFD WITH IMPROVED PHYSICAL MODELING TO CERTIFY PERFORMANCE

CFD VALIDATION REQUIREMENTS



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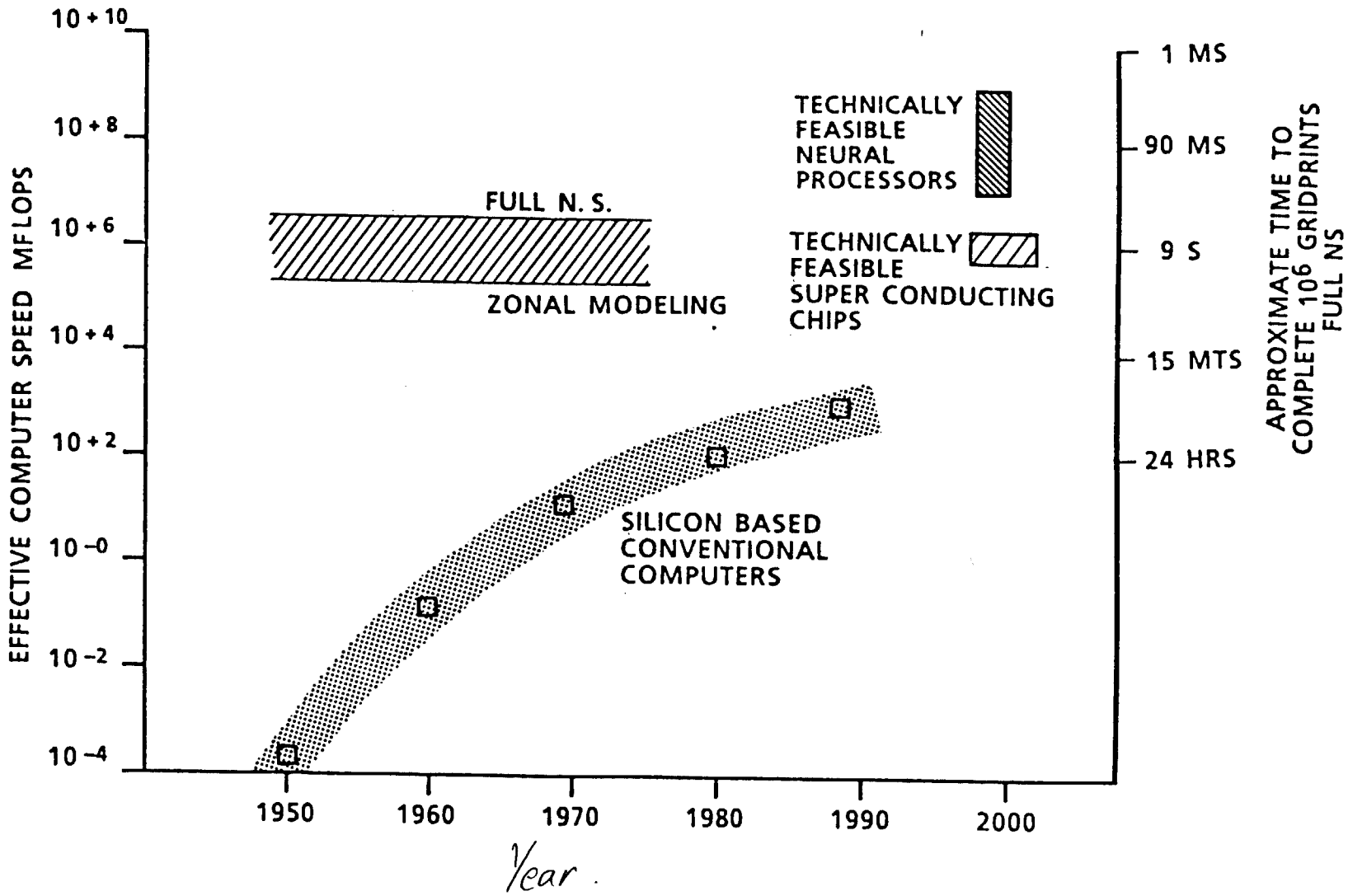
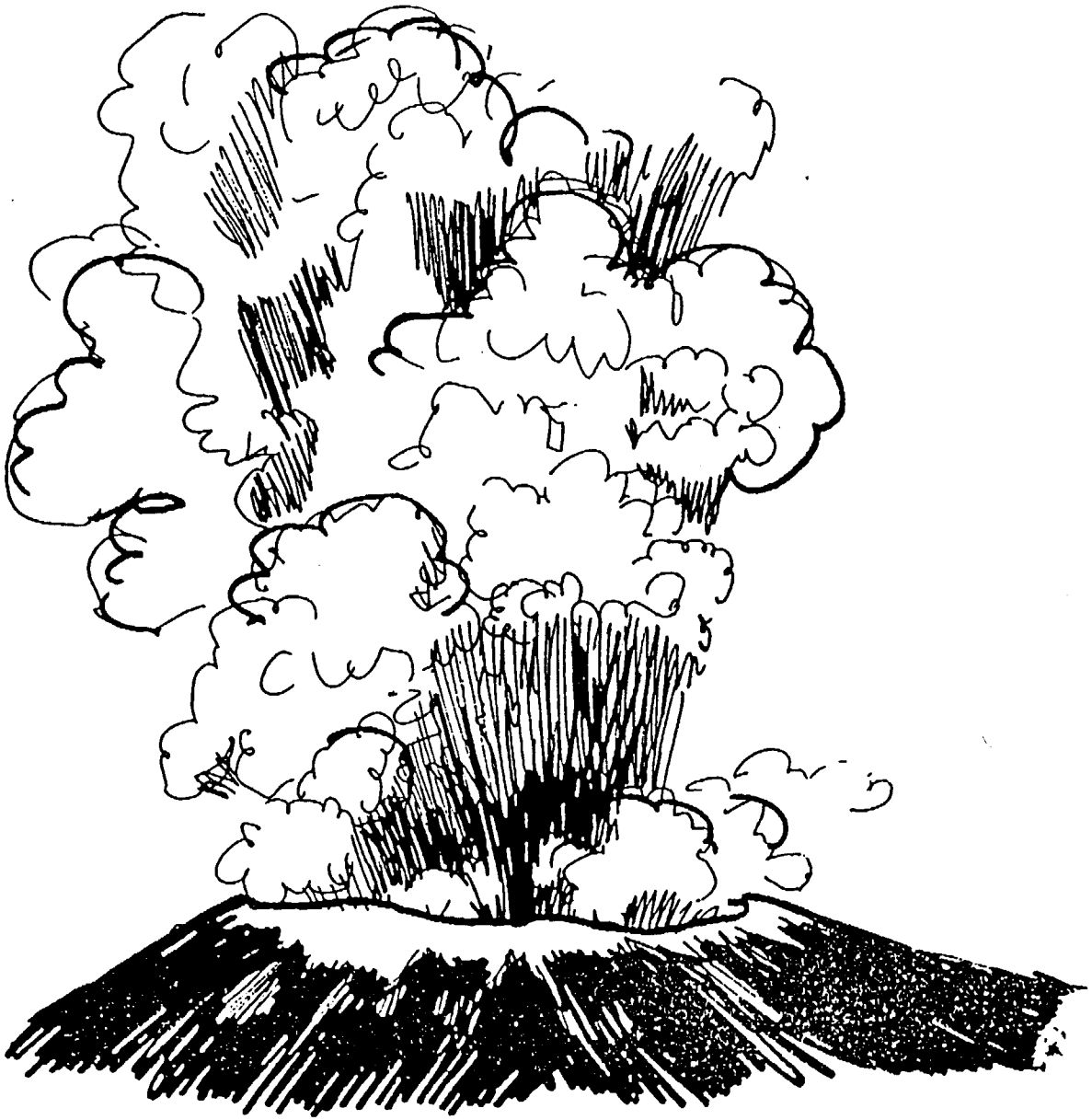
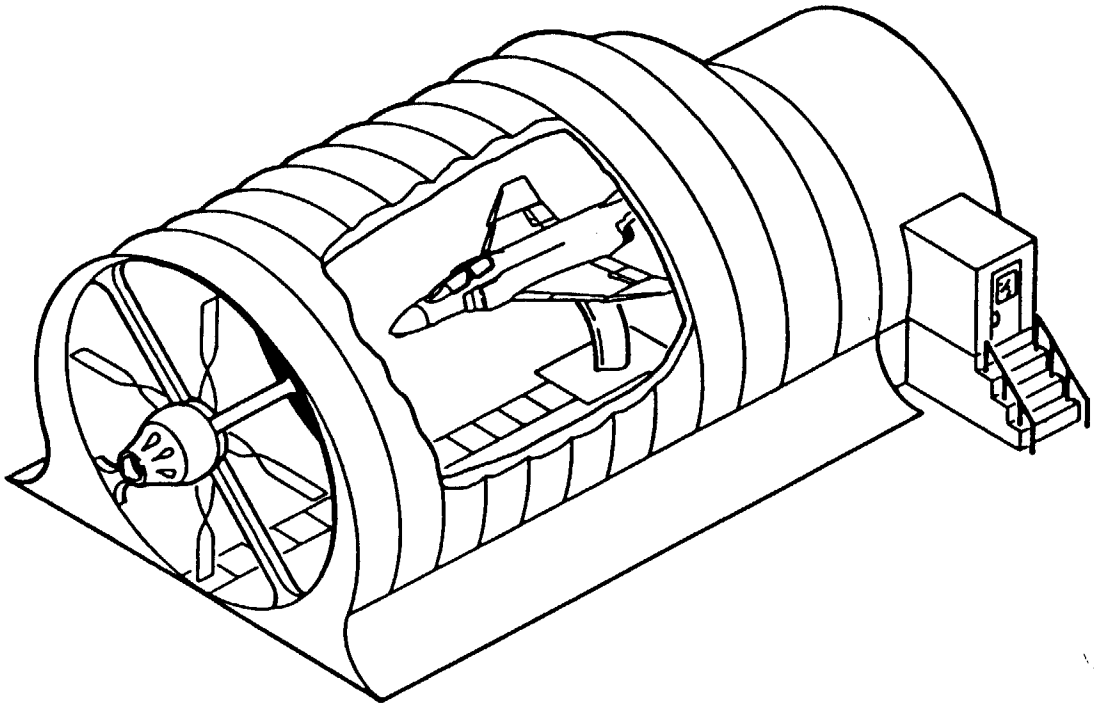
COMPUTER CAPABILITIES



MOUNT ST. HELENS



VALIDATION PROCESS – WIND TUNNEL ROLE



- ENHANCE THE CFD MATURATION PROCESS
- YIELD RESULTS WITH CERTIFIED ERROR ANALYSIS

BENCHMARK EXPERIMENTS

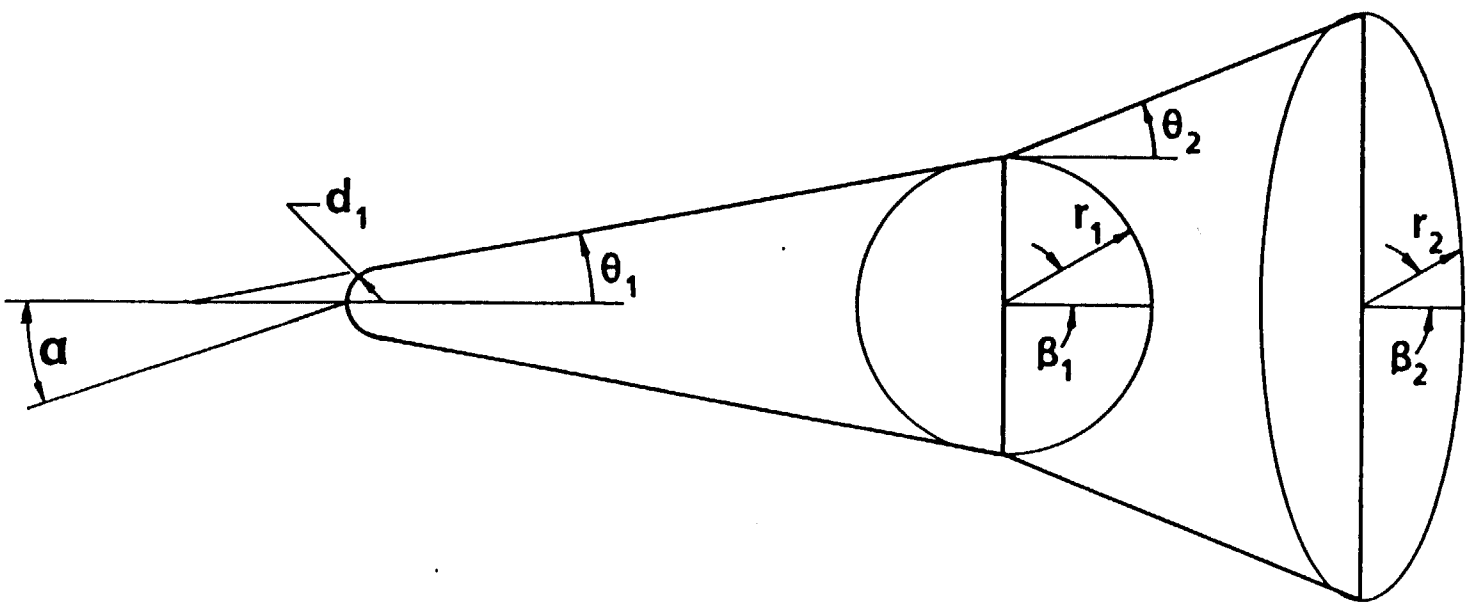
- INGENIOUS "SIMPLE" GEOMETRY
- MEASUREMENTS
  - SURFACE: PRESSURE, TEMPERATURE, SKIN FRICTION, HEAT TRANSFER, ETC.
  - FLOW FIELD: PRESSURE, VELOCITY, TEMPERATURE, MEAN/FLUCTUATING, SPECIES ETC.
  - FORCE: LIFT, DRAG, MOMENT, ETC.
- MEASUREMENT TYPES
  - INTRUSIVE (PROBES, RAKES ---)
  - NON-INTRUSIVE (INTERFEROGRAM, LASER, FLUORESCENCE, ELECTRON BEAM ---)
- FACILITY CALIBRATION
  - WALL AND FREE STREAM
  - NOISE / TURBULENCE LEVEL
  - ACCURACY / REPEATABILITY

BENCHMARK

ELEMENTS (M>1)

FEATURES

- SIMPLE CONFIGURATION / GEOMETRICALLY REPEATABLE
- AXIALLY SYMMETRIC / THREE DIMENSIONAL
- UNSEPARATED / SEPARATED
- LAMINAR / TURBULENT
- LIFTING / NON-LIFTING
- CHEMISTRY



ADVANTAGES OF MATURE CFD TECHNOLOGY

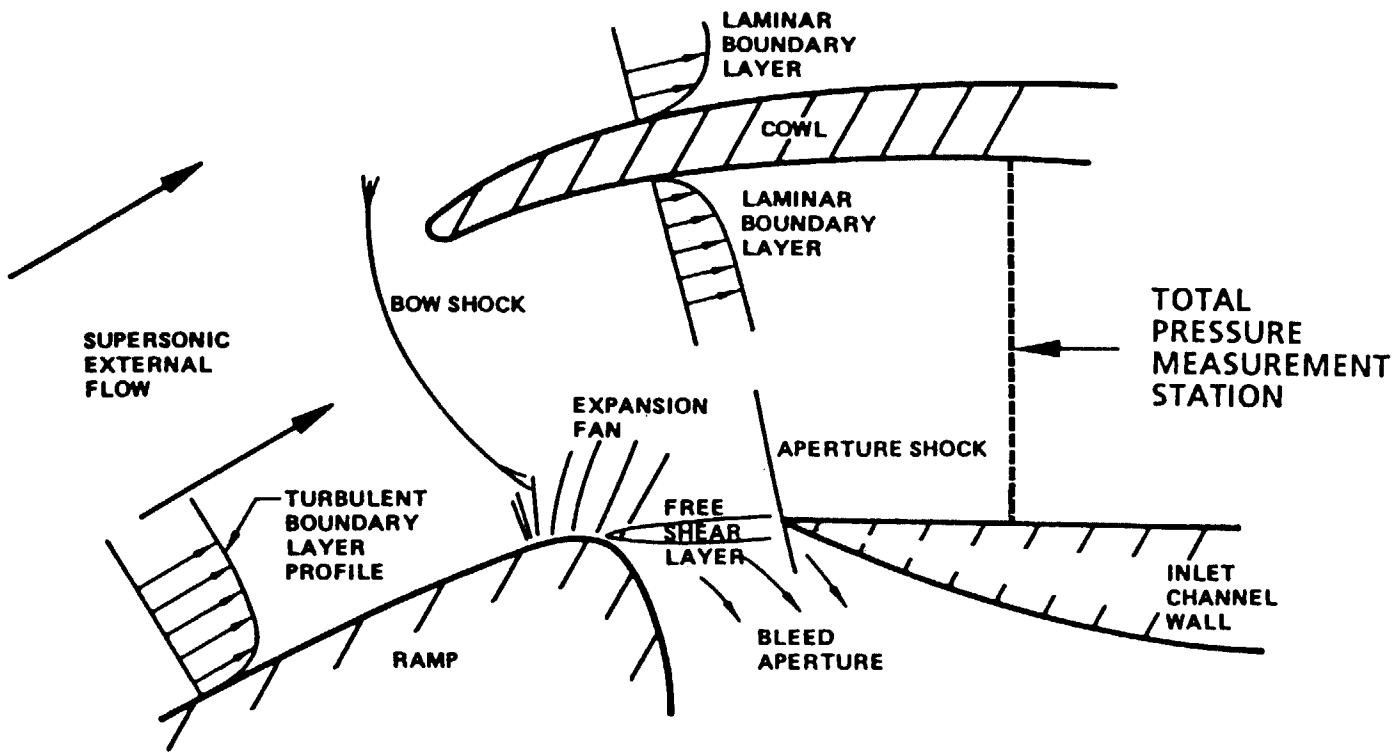
- GENERATES AVENUES TO EXAMINE AIRPLANE CONCEPTS BEYOND CONVENTIONAL VIEWS
- MINIMIZES FULL SCALE TESTING OF CONCEPTS
- PROVIDES INSIGHT TO ALTERNATIVE NEW AIRCRAFT CONFIGURATIONS

⇩

EFFECTIVE USE OF SIMPLER NUMERICAL CODES FOR OPTIMUM CONFIGURATION DESIGN

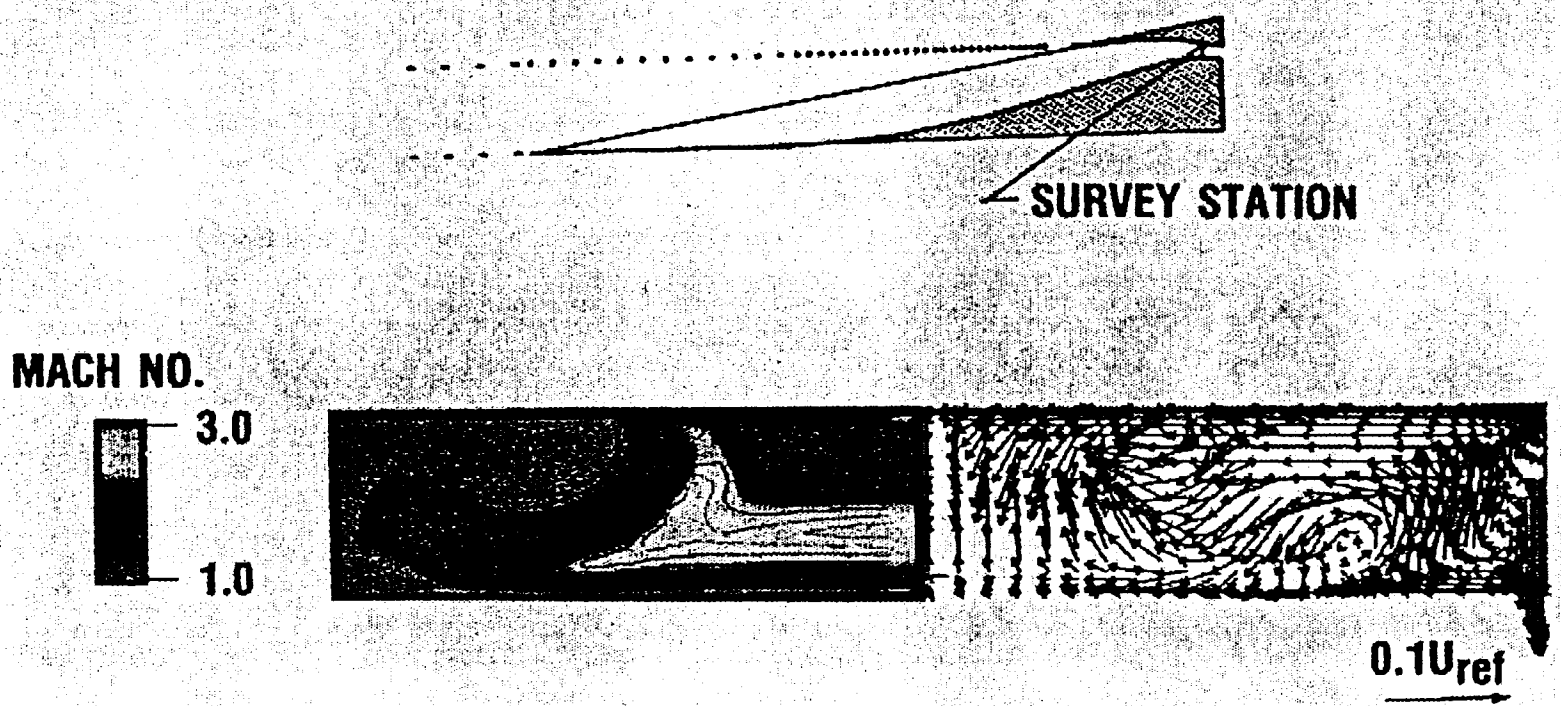
CFD IN DESIGN

FLOW FIELD FEATURE



MACH 5.0 HYPERSONIC INLET

MACH NUMBER AND SECONDARY VELOCITY VECTORS



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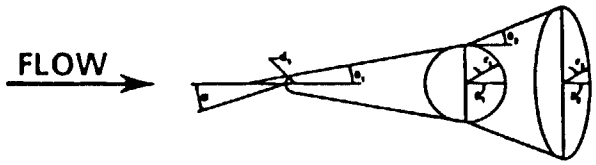
CFD MATURATION



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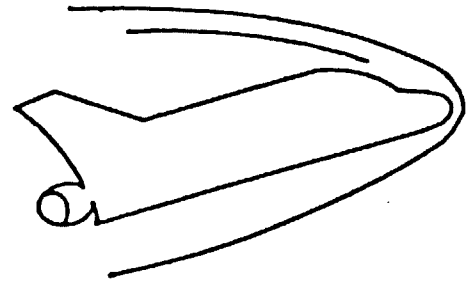


⇒ CFD VALIDATION

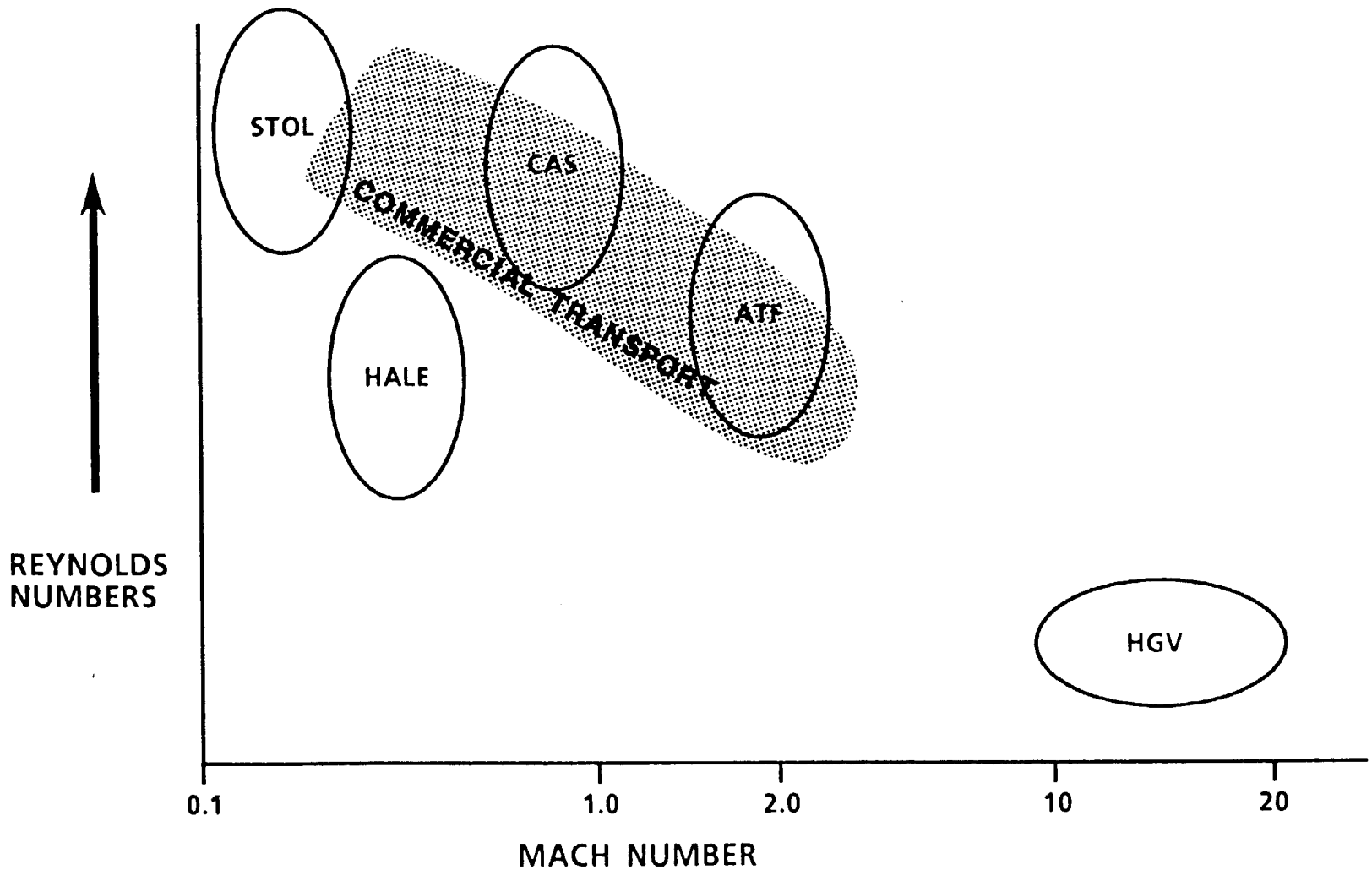
BENCH MARK EXPERIMENT + CFD COMPONENT VALIDATION

- NUMERICAL
- PHYSICAL
- CODING (CERTIFIED)

VALIDATION OF APPLICATION PROCESS

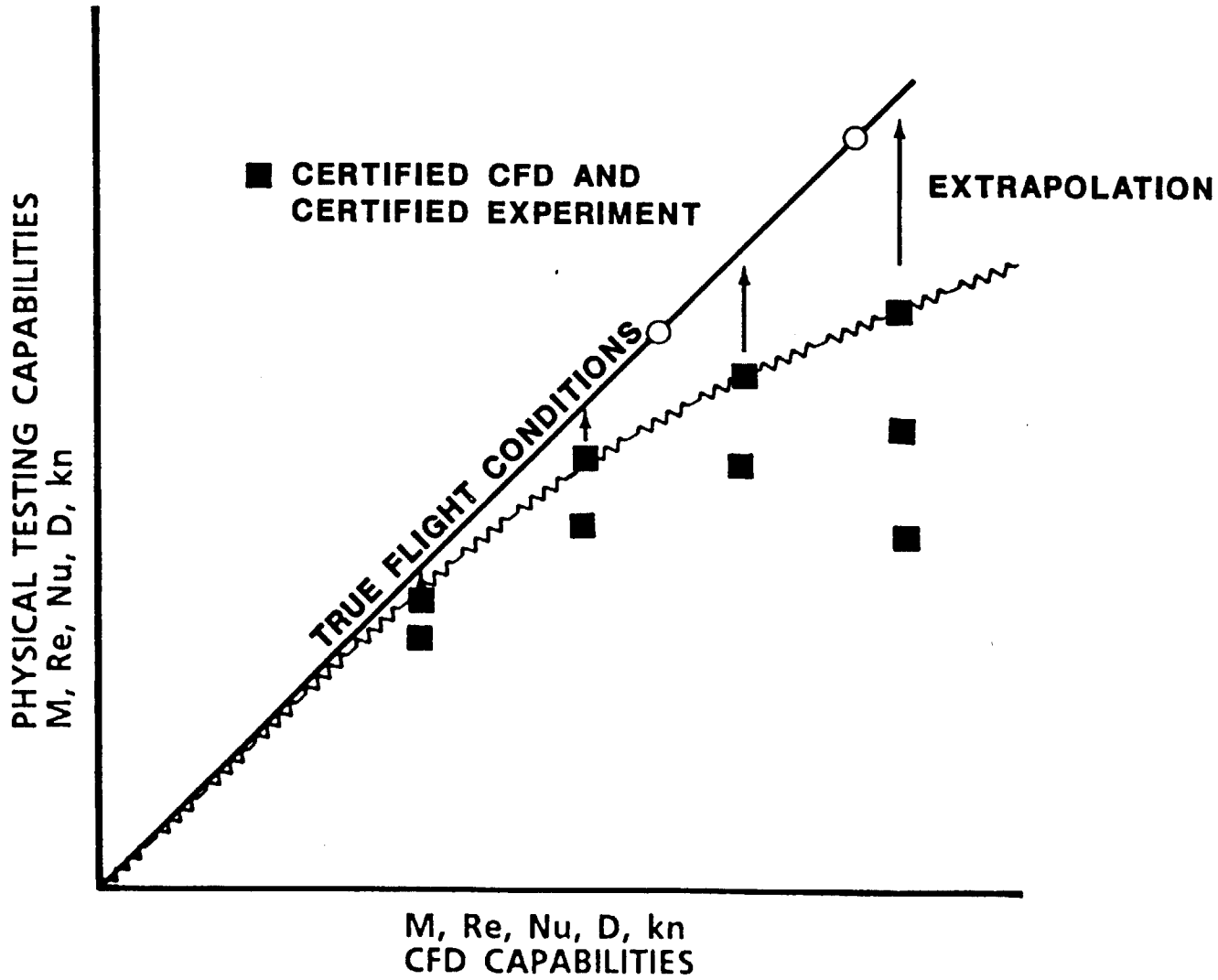
- GLOBAL CONSERVATION
- APPROPRIATE GRID
- CERTIFIED ACCURACY

CFD VALIDATION OPPORTUNITIES



CFD EXTRAPOLATION

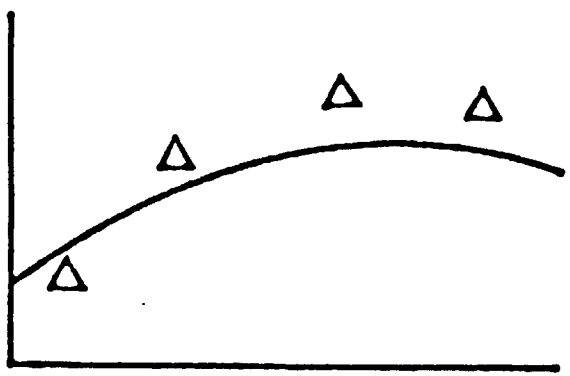
BASED UPON VALIDATION



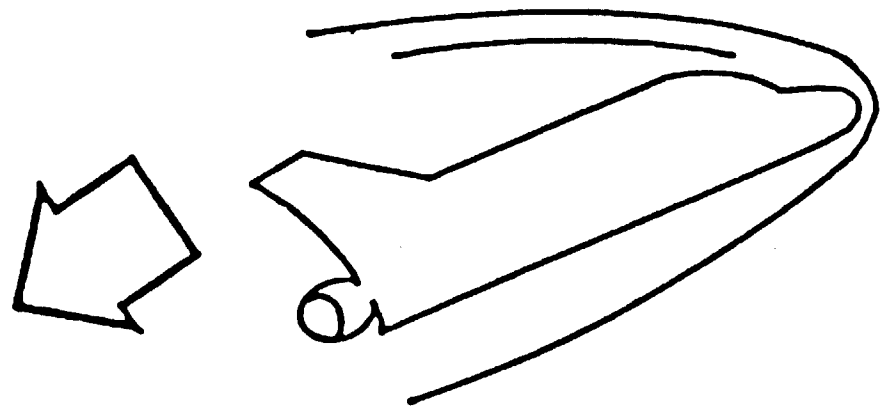
SUMMARY

- VALIDATION OF CERTIFIED CFD PROCESSES AGAINST CERTIFIED EXPERIMENTAL RESULTS
  - OVER RANGE OF BENCHMARKS FOR PHYSICAL PHENOMENON
  - OVER RANGE OF FLIGHT CONDITIONS (M, RE, ETC.)
- APPLICATION OF CERTIFIED CFD PROCESSES TO FLIGHT VEHICLES
  - EXTRAPOLATED WITH HIGH DEGREE OF ACCURACY
- DEVELOPMENT OF OPTIMIZED / IMPROVED VEHICLE DESIGN
  - UTILIZING CERTIFIED CFD PROCESSES

CFD VALIDATION REQUIREMENTS SATISFIED



TEST–THEORY COMPARISON



TESTS OF COMPLEX GEOMETRY FOR CODE VALIDATION

N92-70943

40p

CFD Validation Experiments at the Lockheed-Georgia Company

J.B. Malone
and
A.S.W. Thomas

Lockheed-Georgia Company

GA-7284-1

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CFD Validation Experiments at Lockheed-Georgia

Wings A, B and C - Hinson and Burdges (1979)
Airloads, Surface and Farfield Pressures (AGARD Standard Data Set)

LANN Wing - Malone, Ruo, Horsten, den Boer and Zwaan (1982)
Steady and Unsteady Surface Pressures (AGARD Standard Data Set)

GAW-1 Airfoil - Bradon, Whipkey, Lilley, Jones and Morgan (1983)
Surface Pressures and 2-D LV Flowfield Measurements

CCW Airfoil - Novak and Cornelius (1985)
Surface Pressures and 2-D LV Flowfield Measurements

GA-7254-3

CFD Validation Experiments

Propeller Blade - Lepicovsky (1985)
Conditional-Averaged 2-D LV Flowfield Measurements

Generic Fighter Configuration - Novak and Huie (1986)
Airloads and 3-D LV Flowfield Measurements

USB Transport Configuration - Cornelius and Whipkey (1987)
Surface Pressure and 3-D LV Flowfield Measurements

Generic Hypersonic Vehicle Configuration - Novak and Cornelius (1987)
Afterbody Surface Pressures, Wake Rake Surveys
2-D and 3-D LV Flowfield Measurements

GA-7254-2

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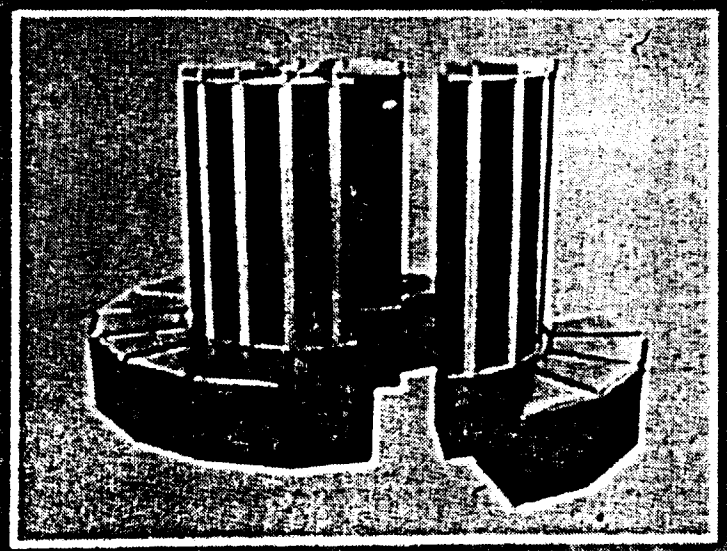
Advanced Aerodynamics Parallel Technology Development

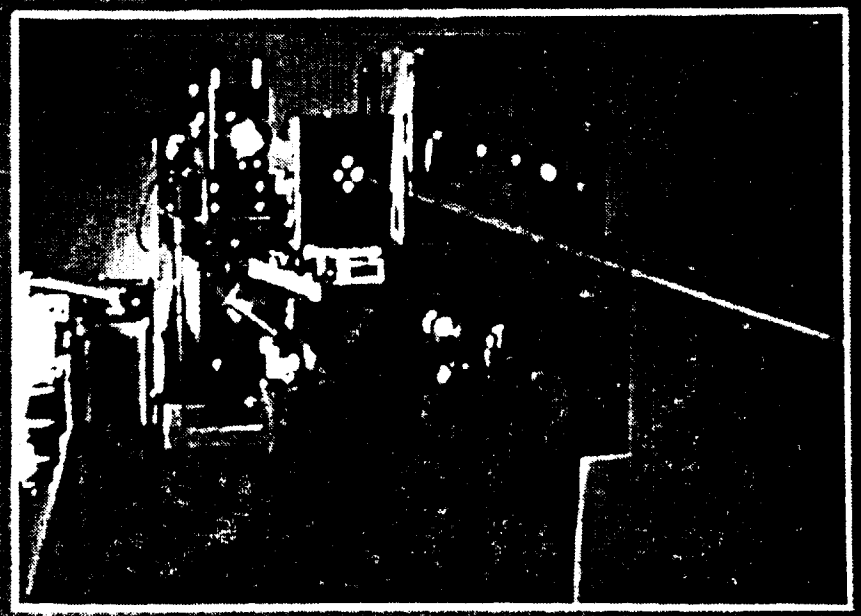
Computational

- 2-D Navier Stokes
- 3-D Euler
- 3-D Navier Stokes
- Grid Generation Methods



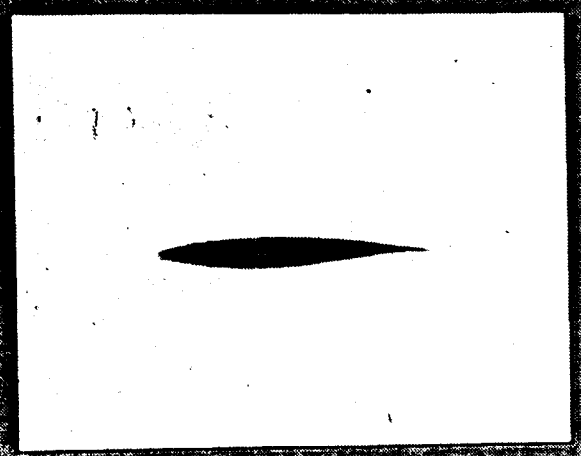
Experimental

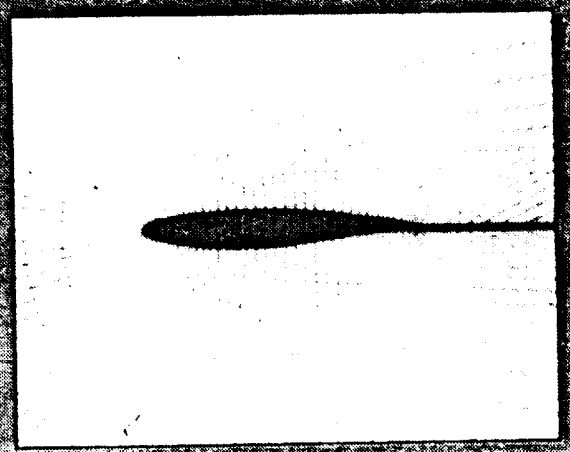
- 2-D Laser Velocimetry
- 3-D Laser Velocimetry
- Particle Imaging Velocimetry

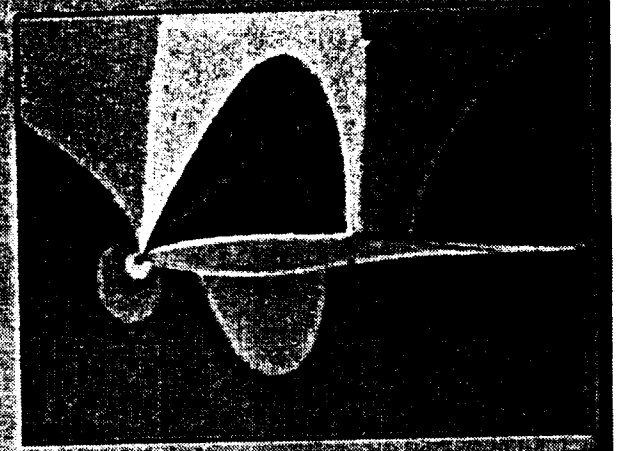


7065-6

Computational Procedure







Geometry Definition

- CATIA/CADAM

Grid Generation

- Wing/Nacelle
- Wing/Fuselage/Nacelle
- Turbojets/Fans
- Ducts
- Specialized Vehicles

Solution Algorithms

- Panel Methods
- Full Potential
- Euler
- Navier-Stokes (ENS3D)

7138-3

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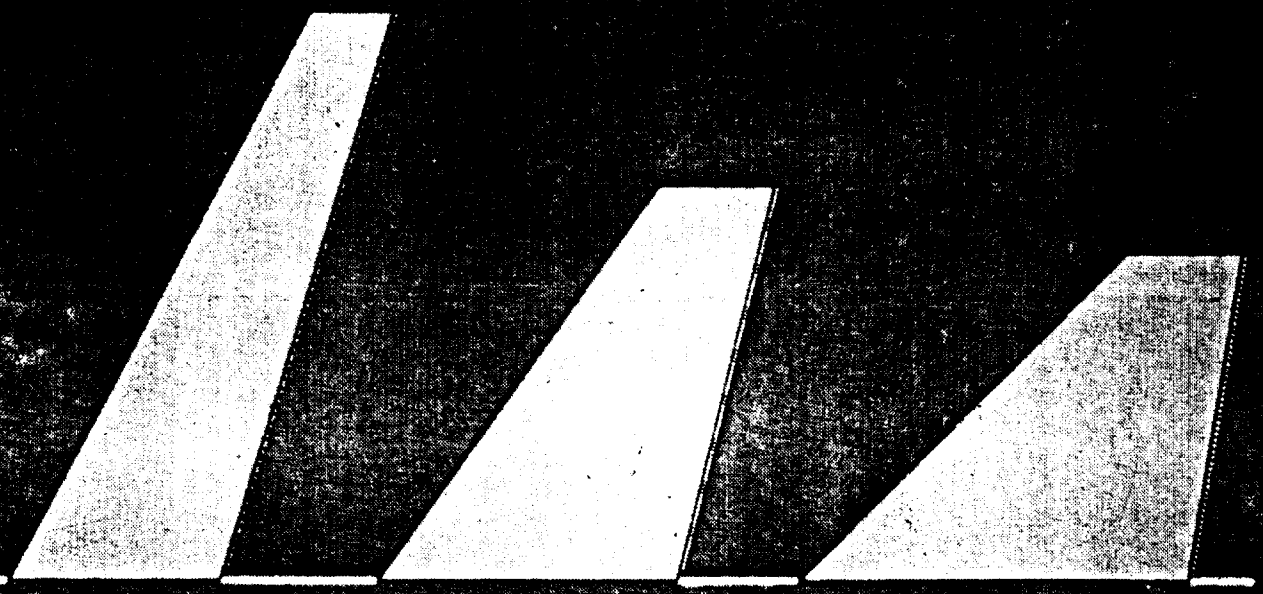
Wings A, B and C Surface and Farfield Pressure Measurements

(Sponsor: AFOSR)



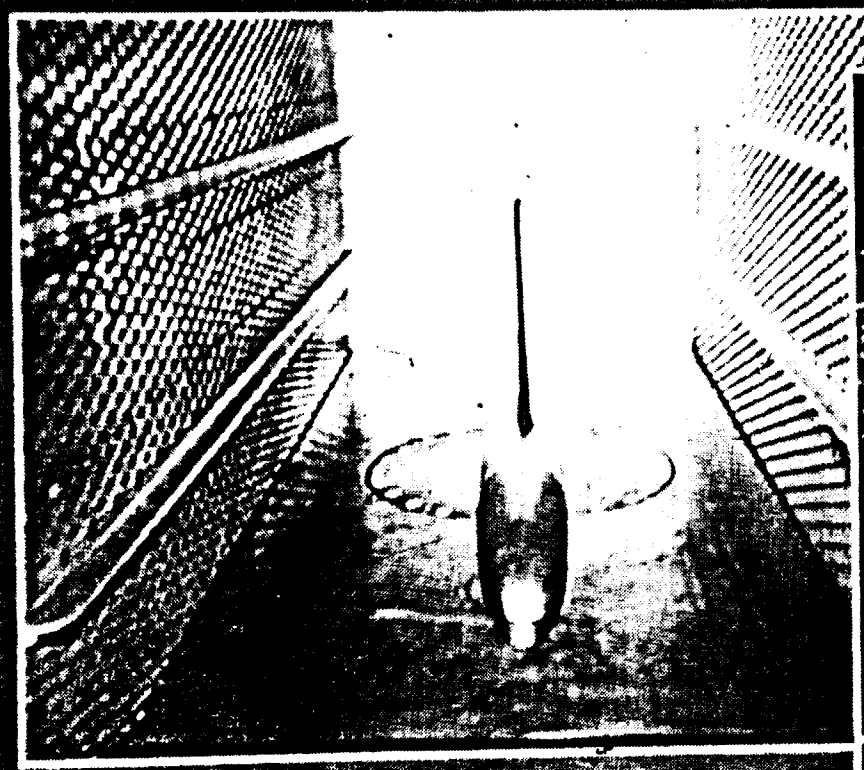
Wing	A	B	C
AR	8.0	3.8	2.6
Λ_{LE}	27°	35°	45°
λ	0.4	0.4	0.3

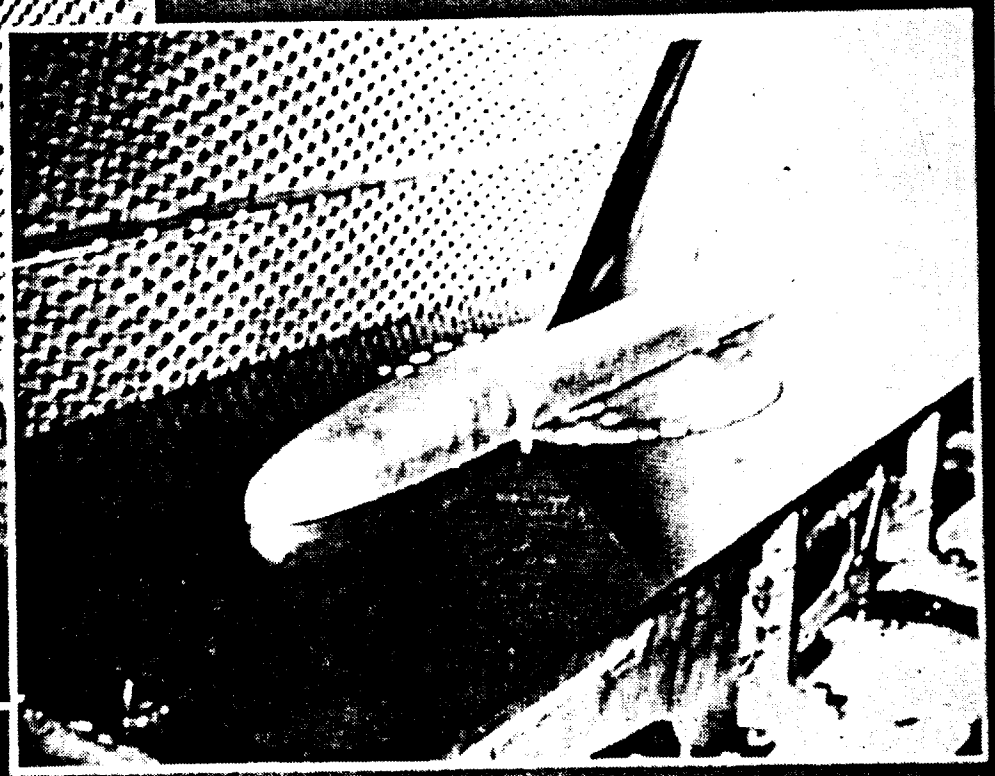
Planforms of Hinson and Burdges Code-Correlation Wings

GA-7254:4

Wing C With Fuselage Installed

Lockheed-Georgia Compressible Flow Wind Tunnel





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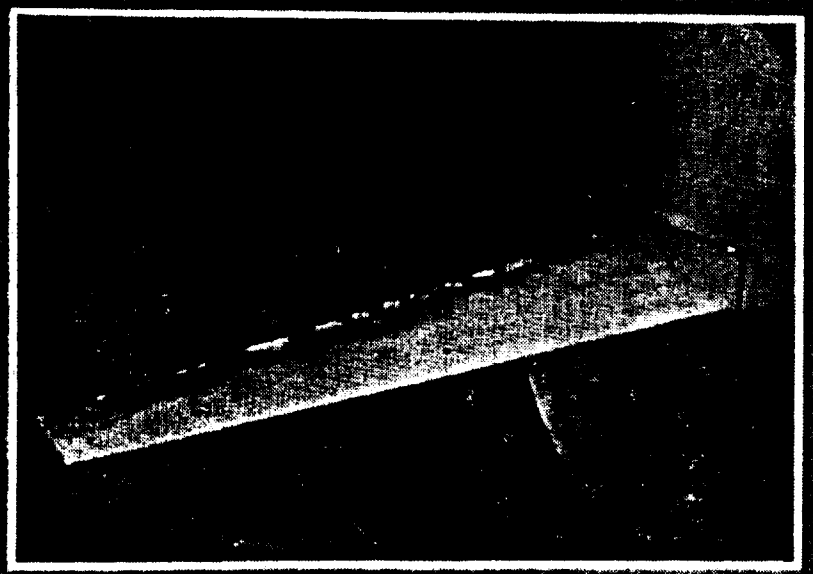
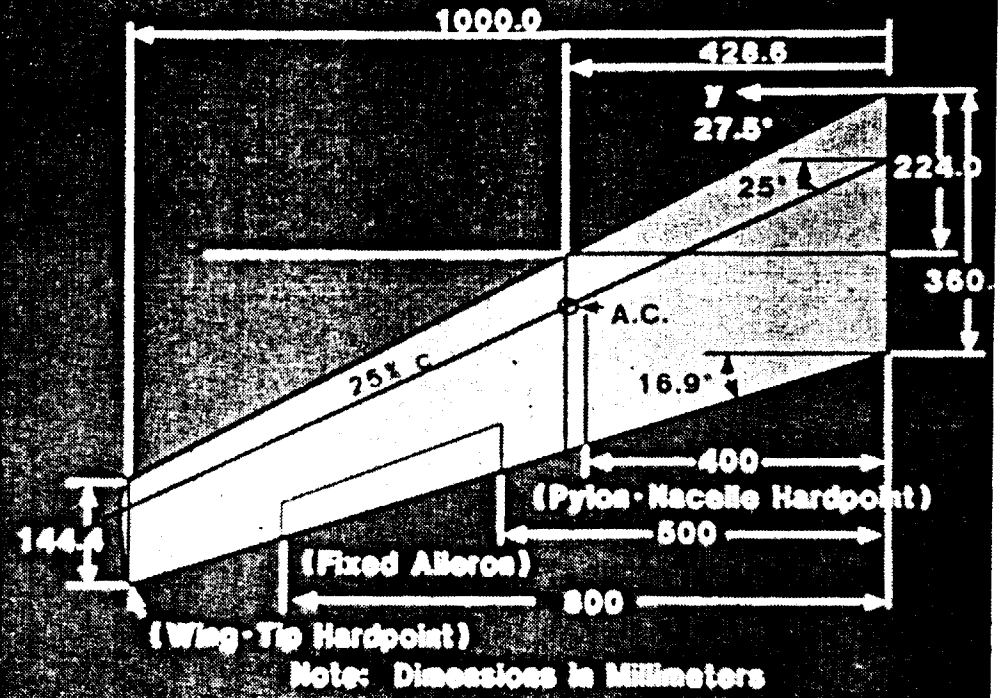
LANN Transport Wing

(Sponsors: Lockheed-Georgia, AFWAL, NASA-Langley, and NLR)



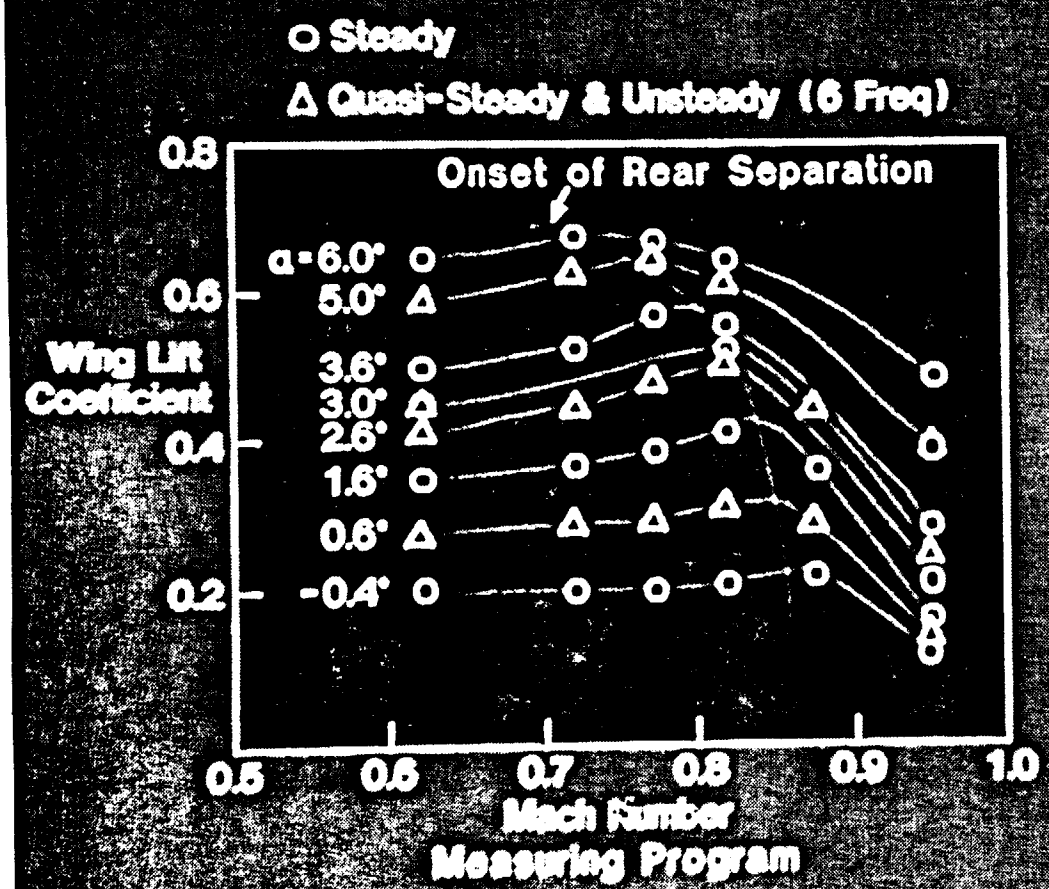
LANN Wing Installed in HST at NLR, Amsterdam

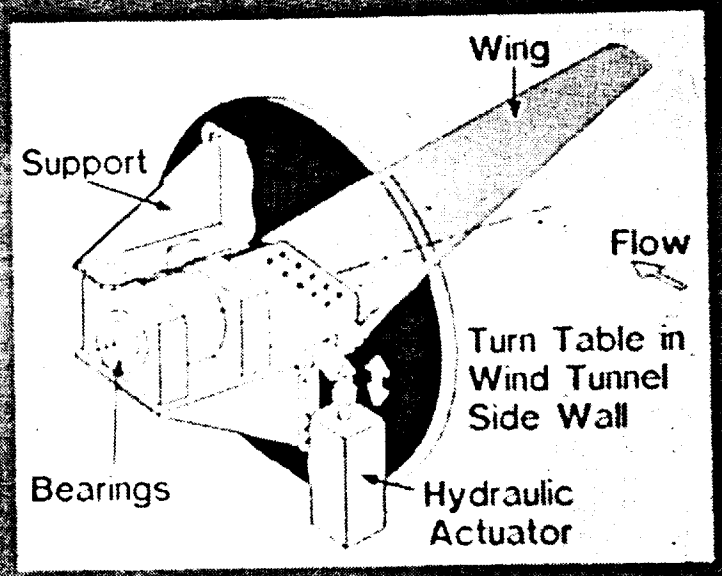


LANN Wing Planform

GA-7284-8

LANN Wing Steady/Unsteady Pressure Measurements

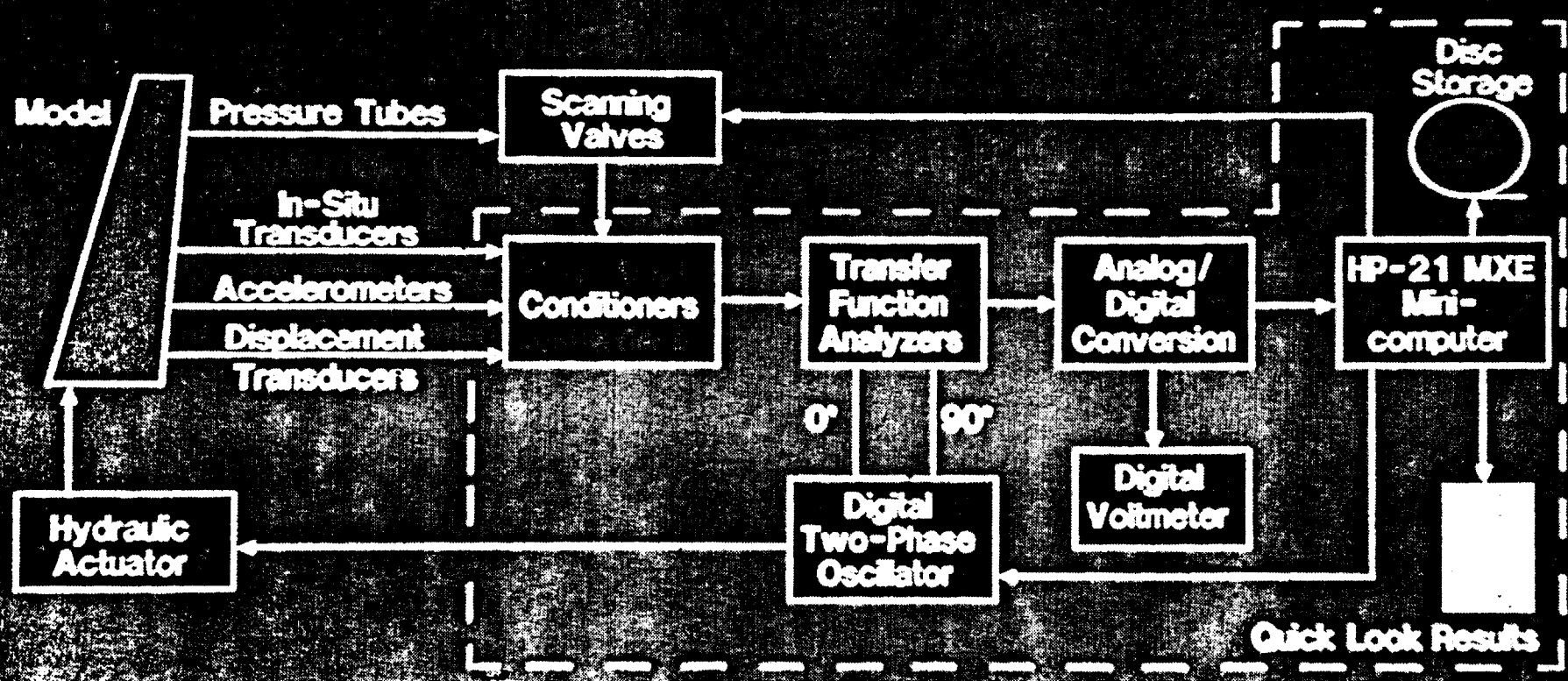




Oscillating Mount Schematic

GA-7254-7

LANN Wing Data Acquisition and Reduction System



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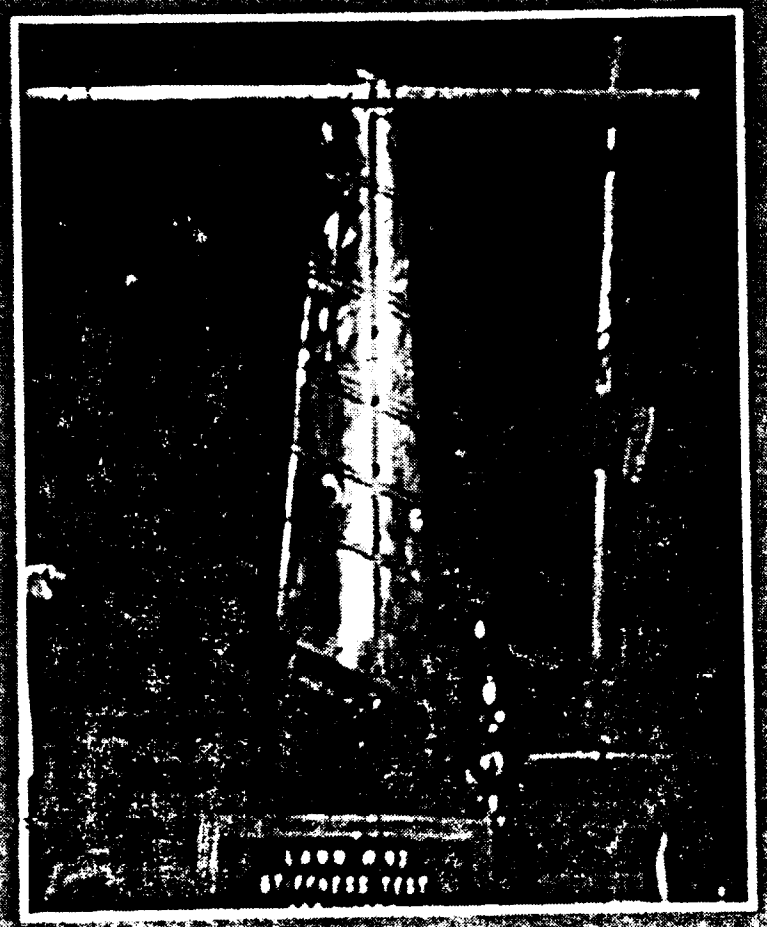
Structural Stiffness Tests Complete LANN Wing Aeroelastic Database



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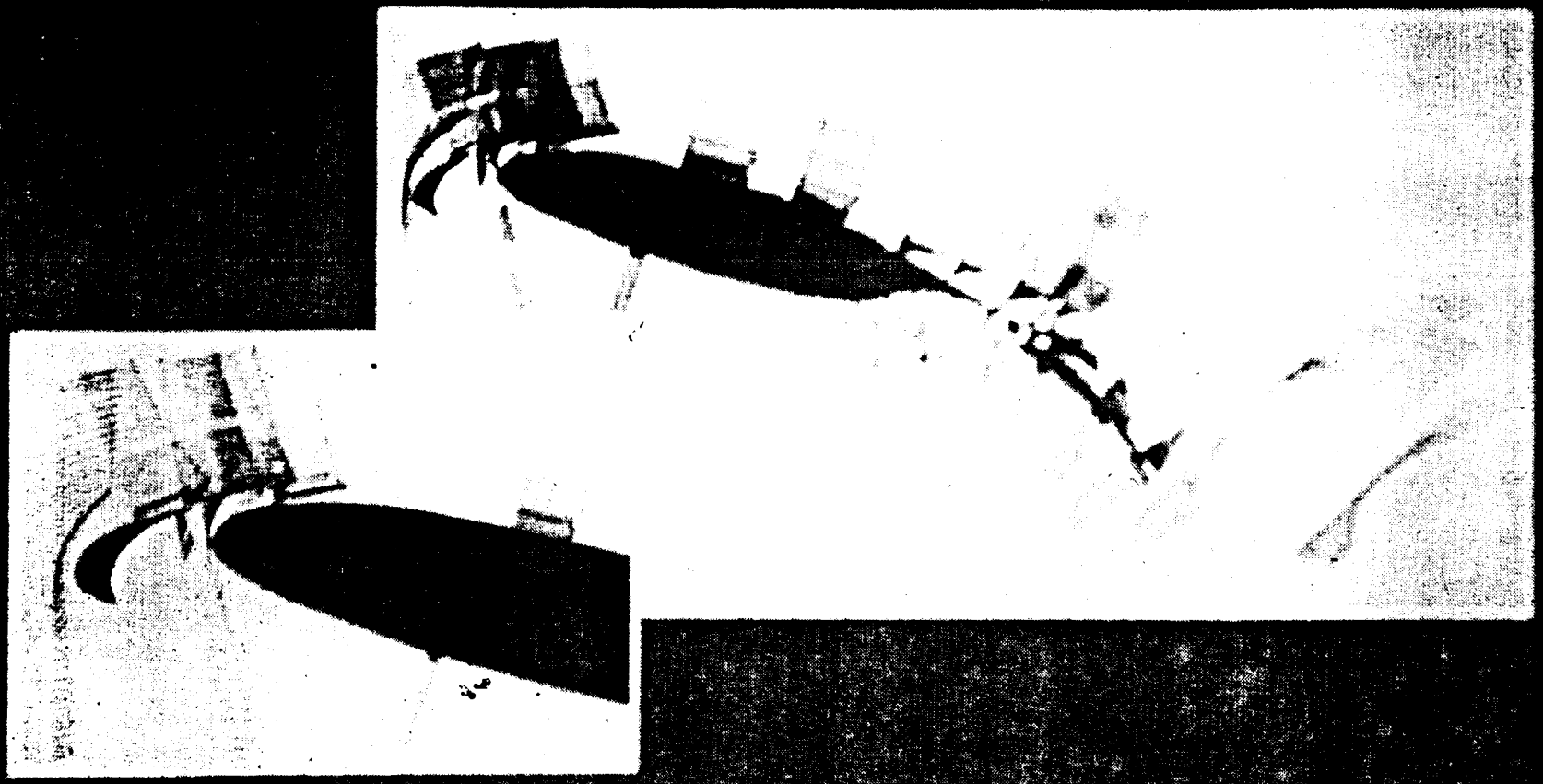
Multi-Element Airfoil System Laser Velocimeter Measurements

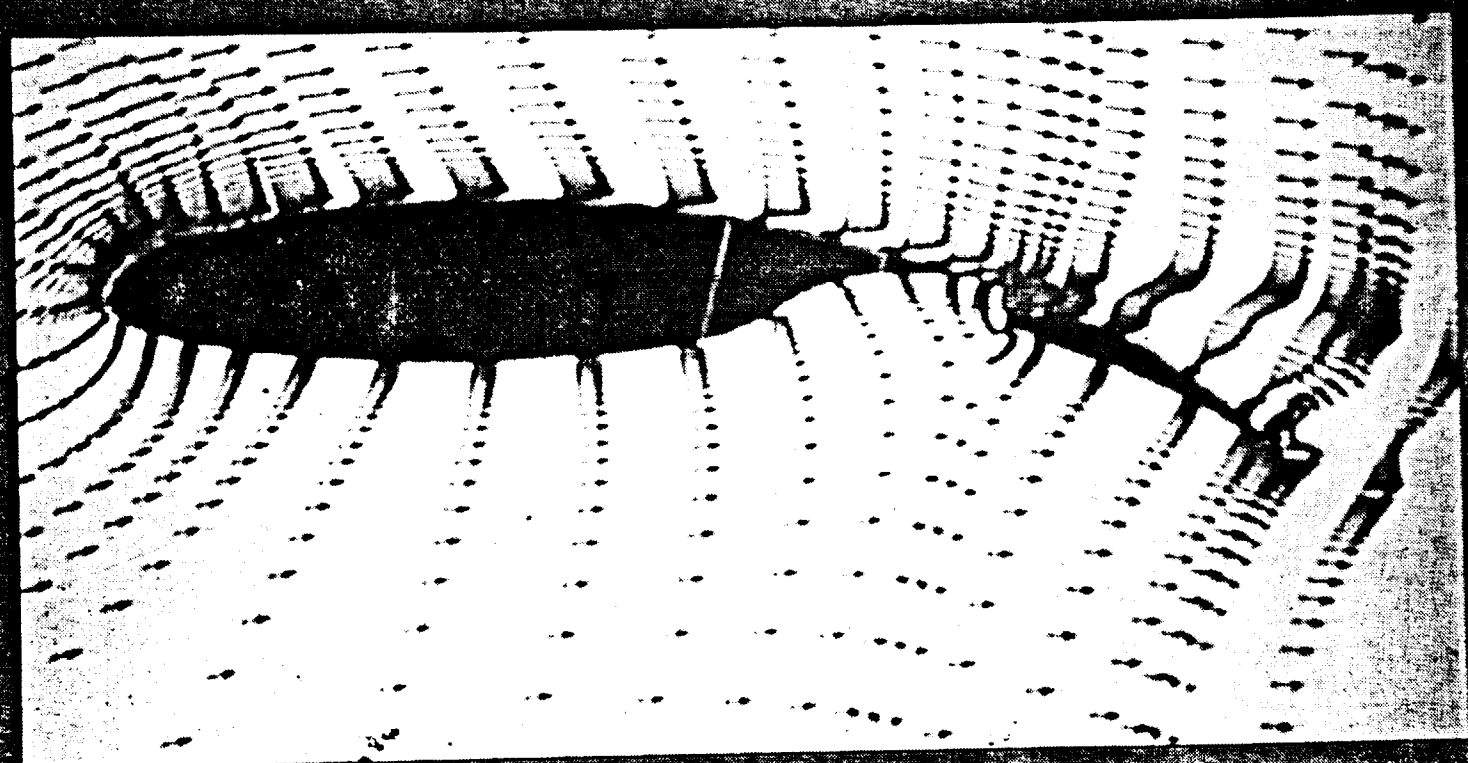
(Sponsor: NASA-Langley)



GA-7284-10

Flowfield Around Slotted Airfoil

Simulation Based on Navier-Stokes Equations



7138-4

GAW-1 Test Configuration Matrix

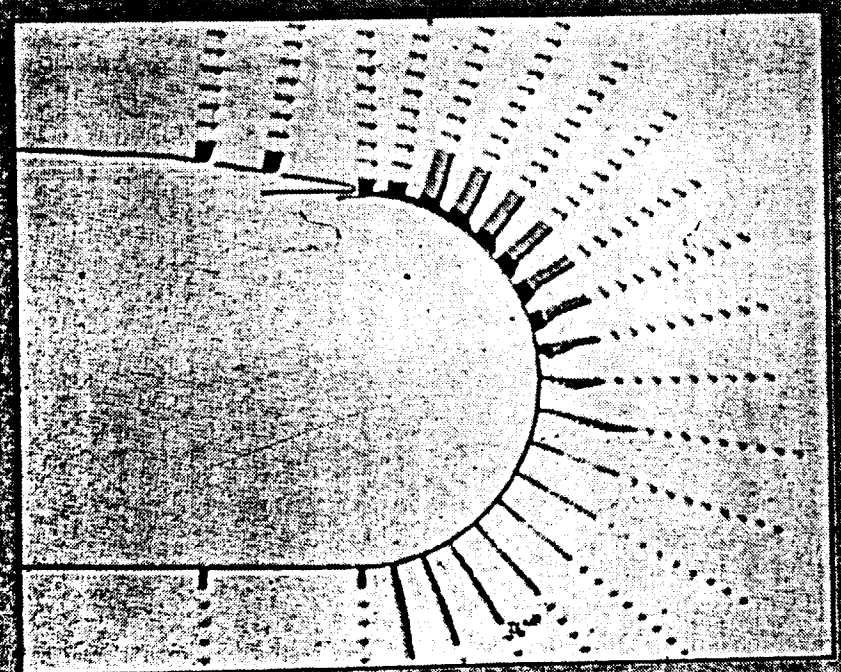
	Configuration	1	2	3	4	5	6
A	Clean Airfoil	α 0	α 4	α 6	α 12	α 16	
B	Flapped δ_f 30	(G C)F 0.04	(OH C)F 0.0		(G C)F 0.025	(OH C)F 0.0	
		α 4	α 8	α 12	α 4	α 12	
C	Flapped δ_f 40	(G C)F 0.015	(OH C)F 0.025		(G C)F 0.015	(OH C)F 0.0	
		α 4	α 8	α 10	α 4	α 8	α 11
D	Slatted δ_s 27	(G C)S 0.023	(OH C)S 0.028				
		α 18	α 22	α 24			
E	Flapped & Slatted δ_s 42 δ_f 30						
		α 12	α 14	α 16			
F	Flapped & Slatted δ_s 42 δ_f 40						
		α 6	α 10	α 14			

GA-7266-11

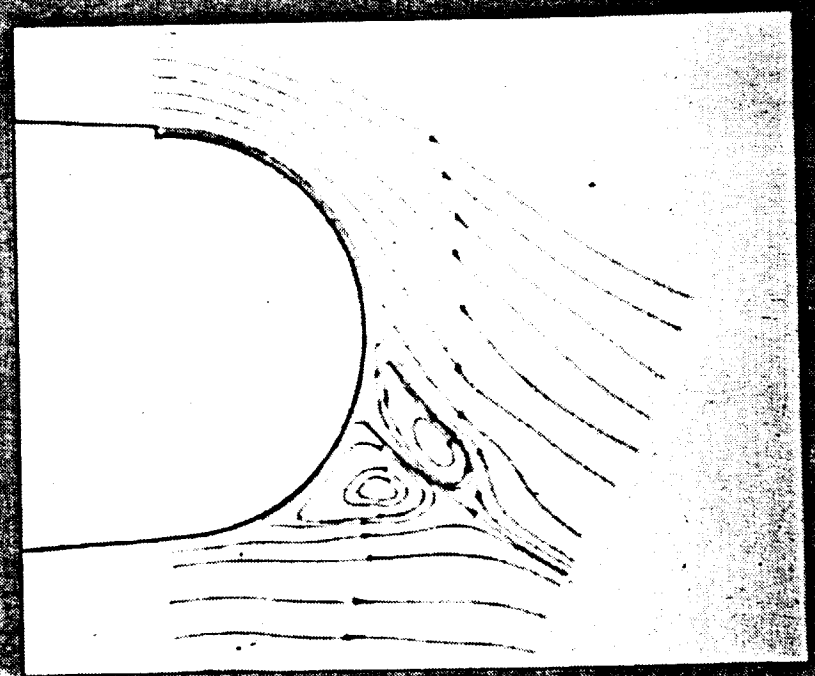
Laser Velocimeter Surveys of Circulation Control Wing

(Sponsor - DARPA)

Velocity Vectors



Streamlines



7136-9

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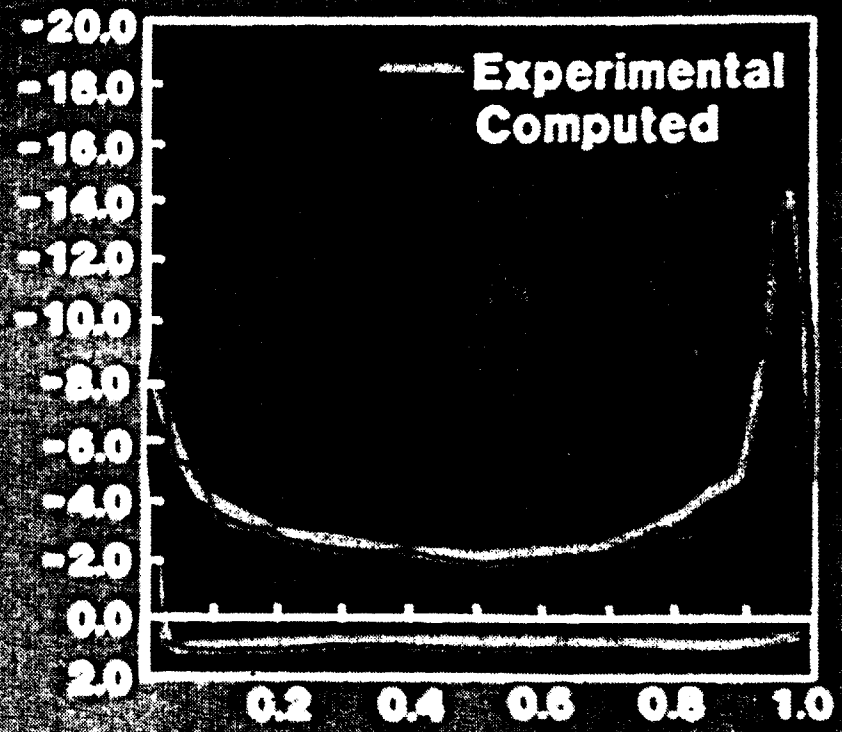
Circulation Control for High Lift

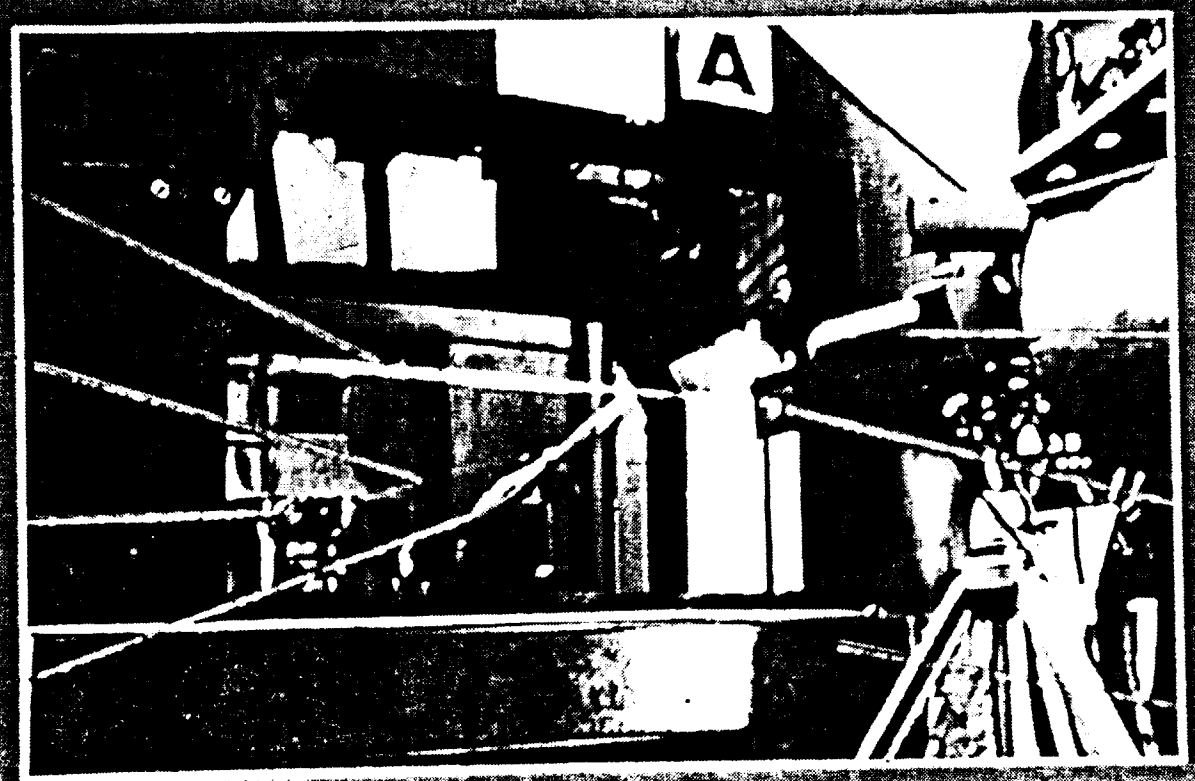
2-D Navier Stokes

Comparison of Experiment and Theory



Laser Velocimeter Surveys of Static Propeller Flowfield

(Sponsor: Lockheed IRAD)



Laser Beams

Triggering Beam

Auxiliary Laser

Propeller Blade

Fog Generator

Triggering Unit

Transmitting Optics

Main Laser

Test Facility

CA-7244-12

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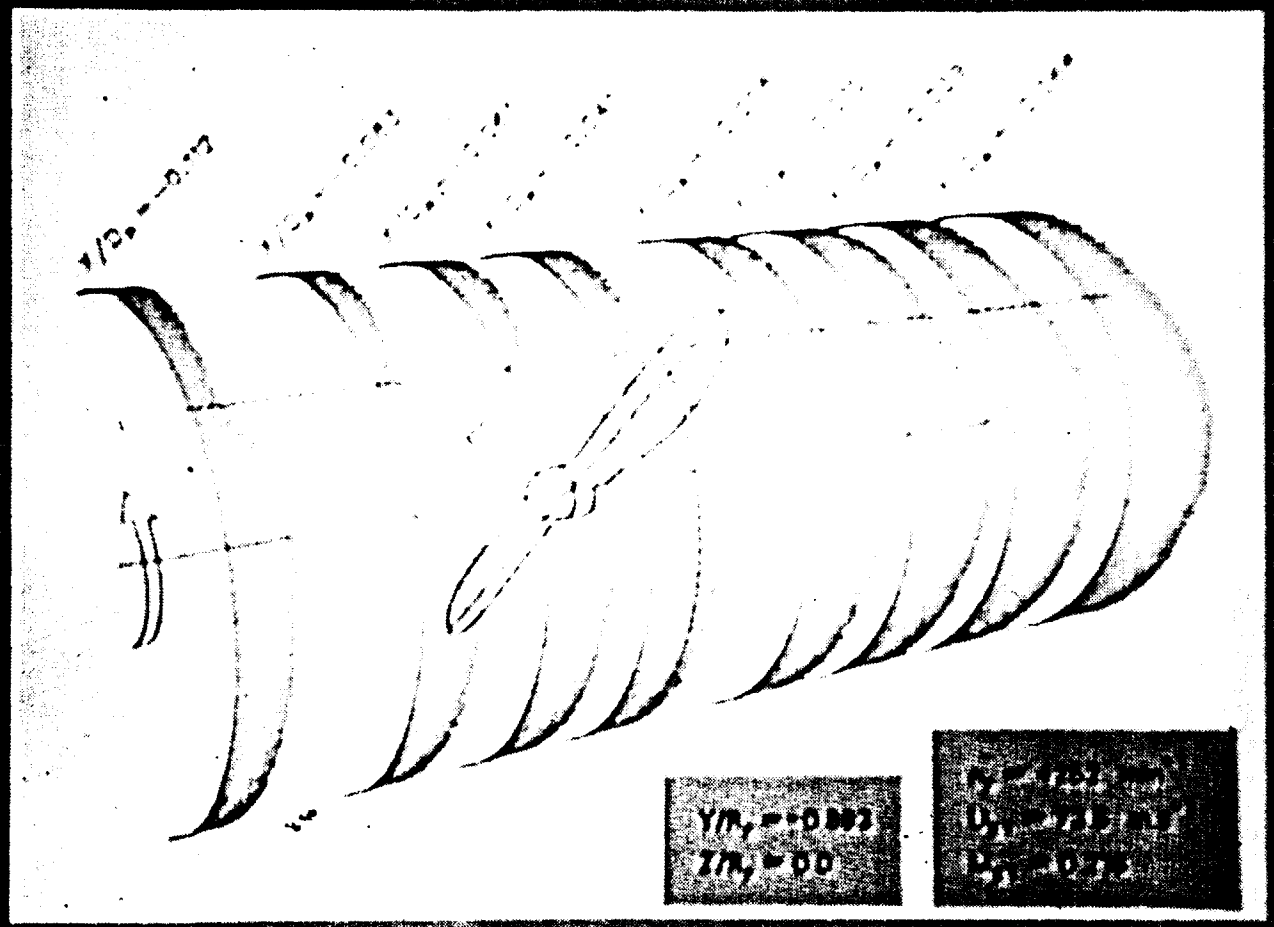
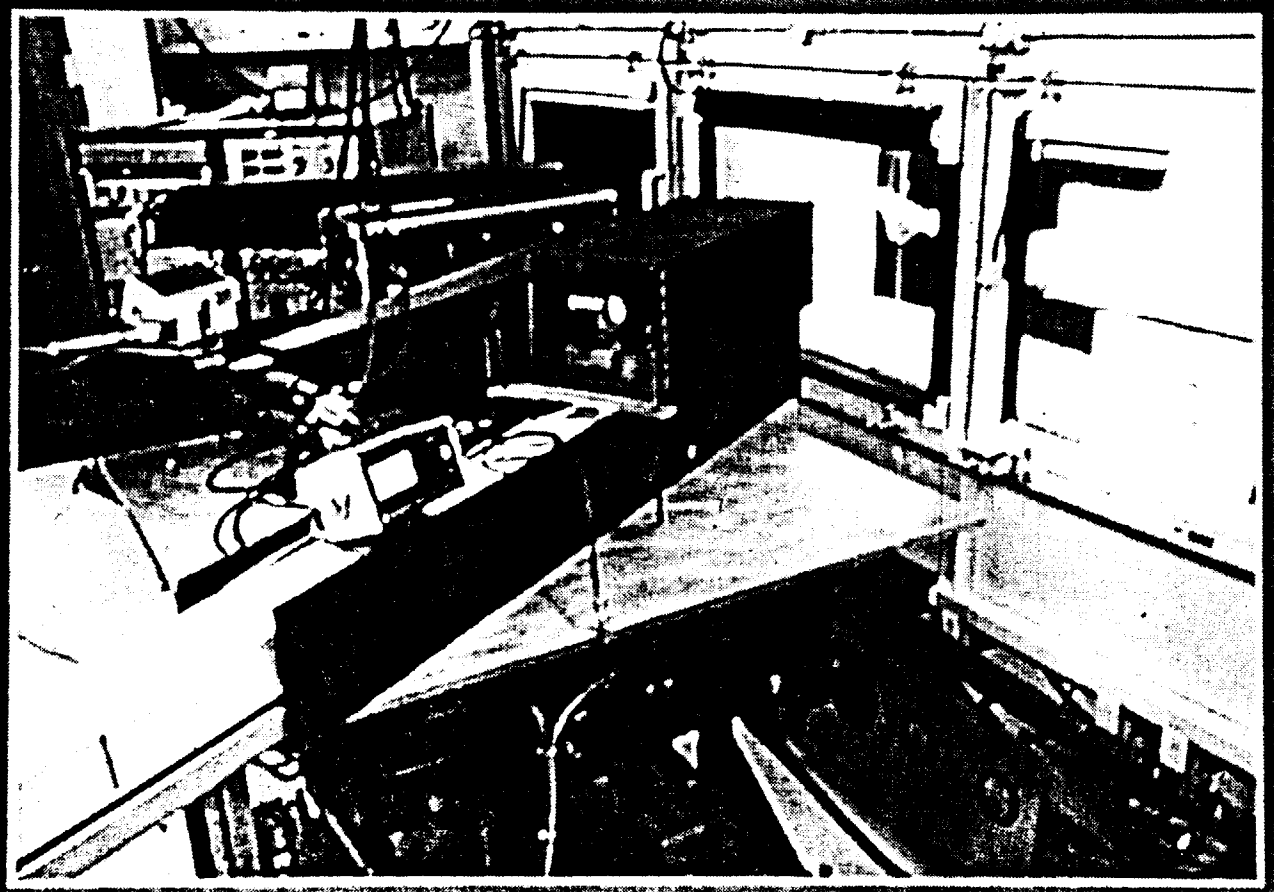
Propeller Axial Velocity Flowfield



GA-7164-13

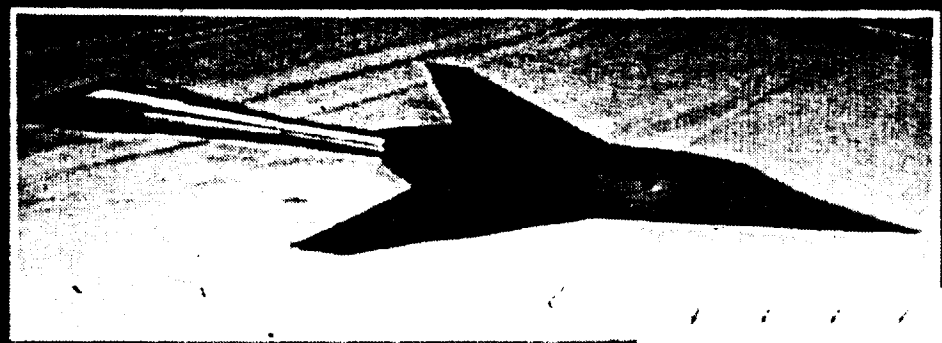
3-D Laser System in Lockheed-Georgia Low Turbulence Wind Tunnel

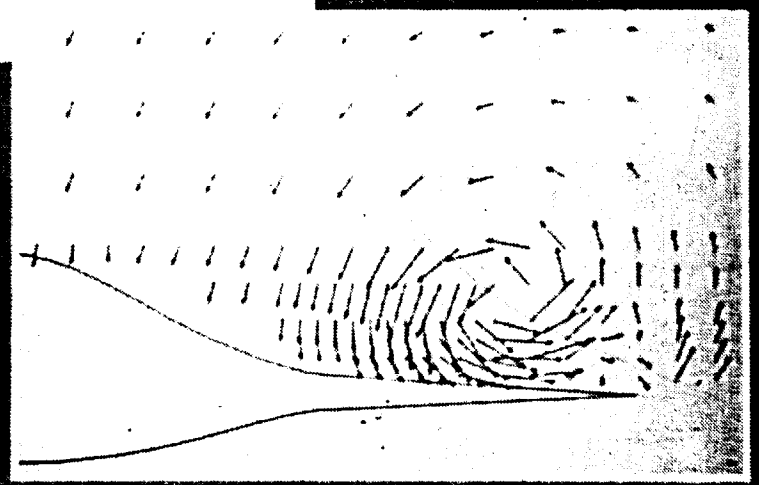


GA-7254-14

High Angle-of-Attack Aerodynamic Evaluations

(Sponsor: Lockheed IRAD)





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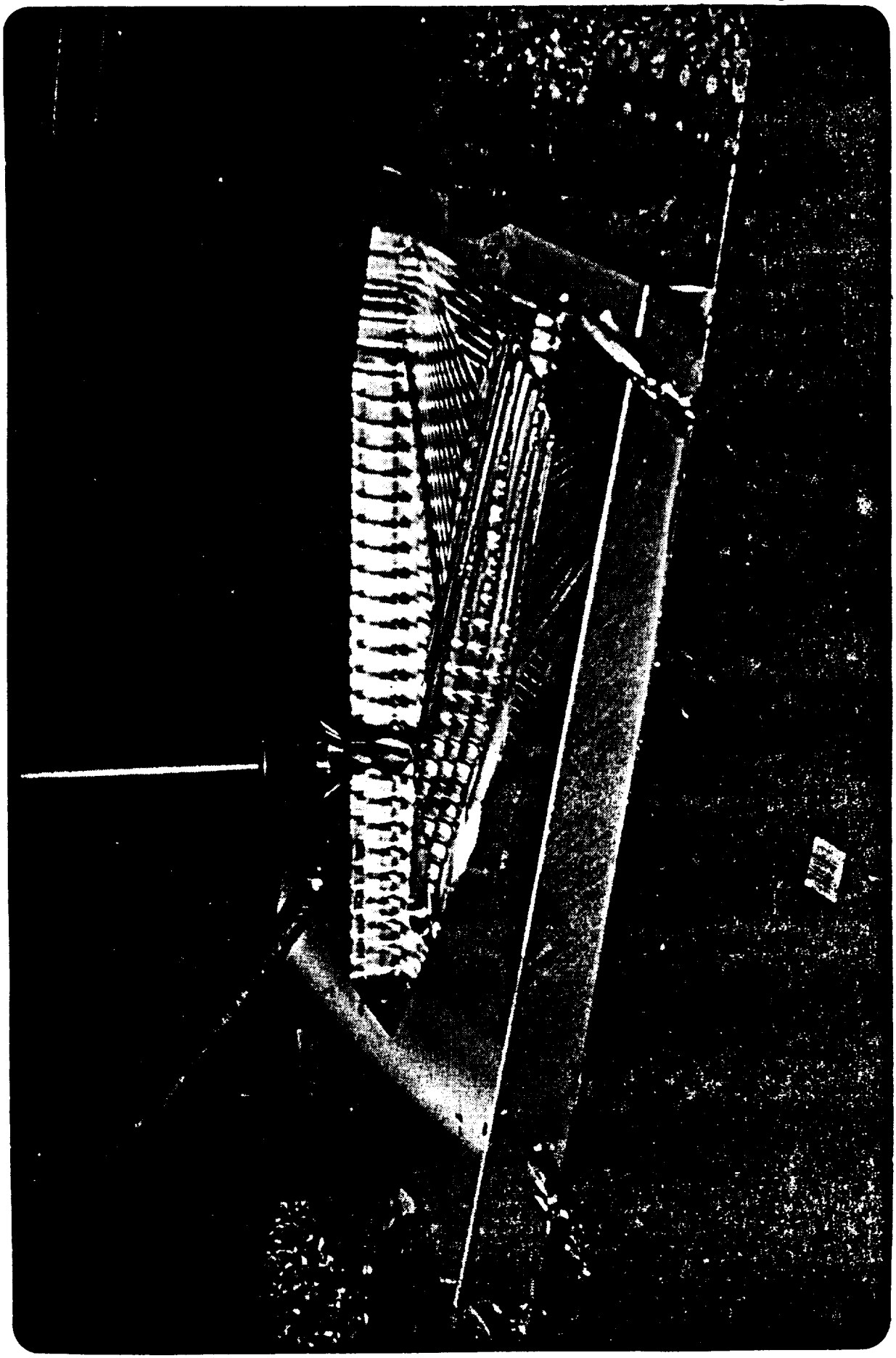

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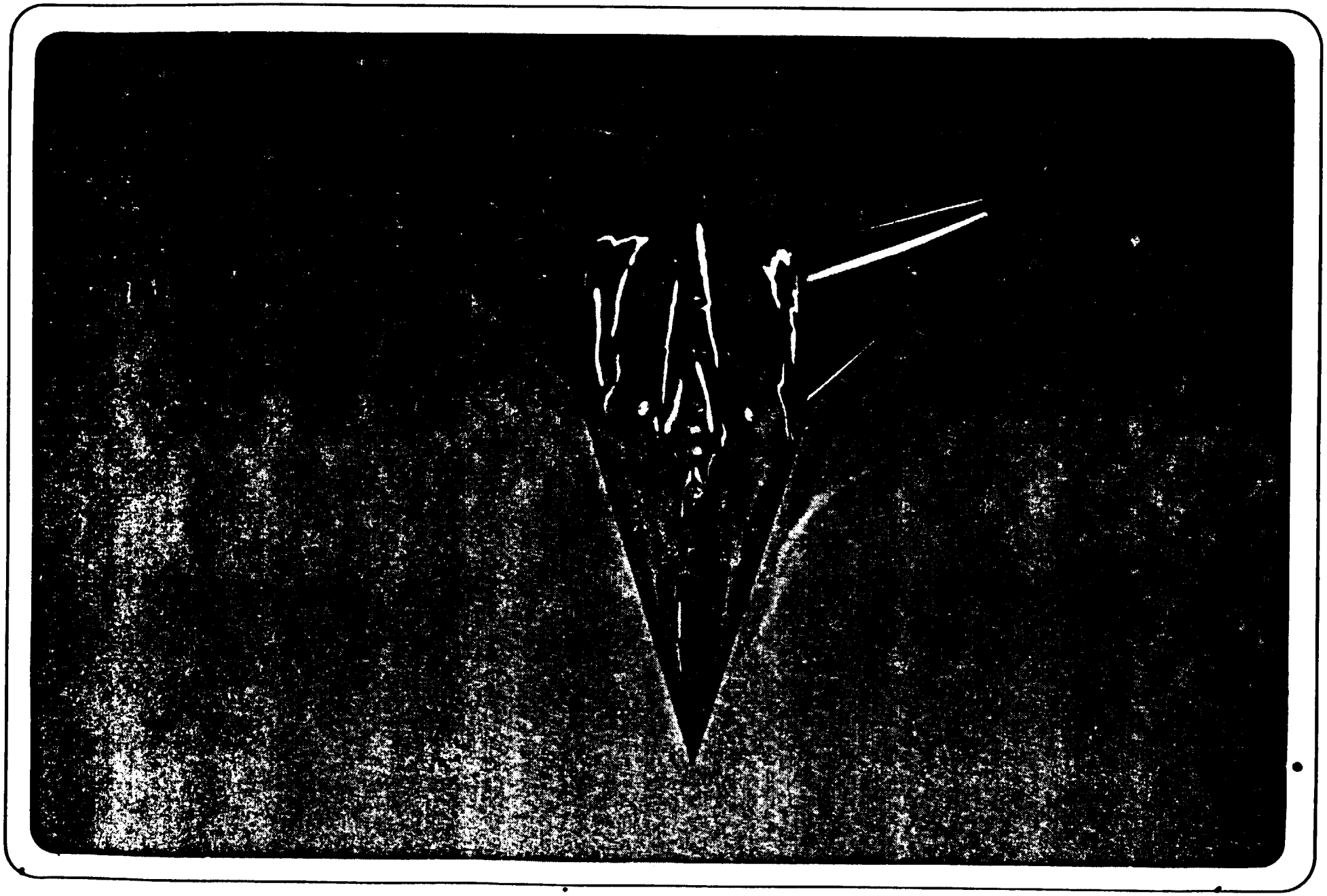
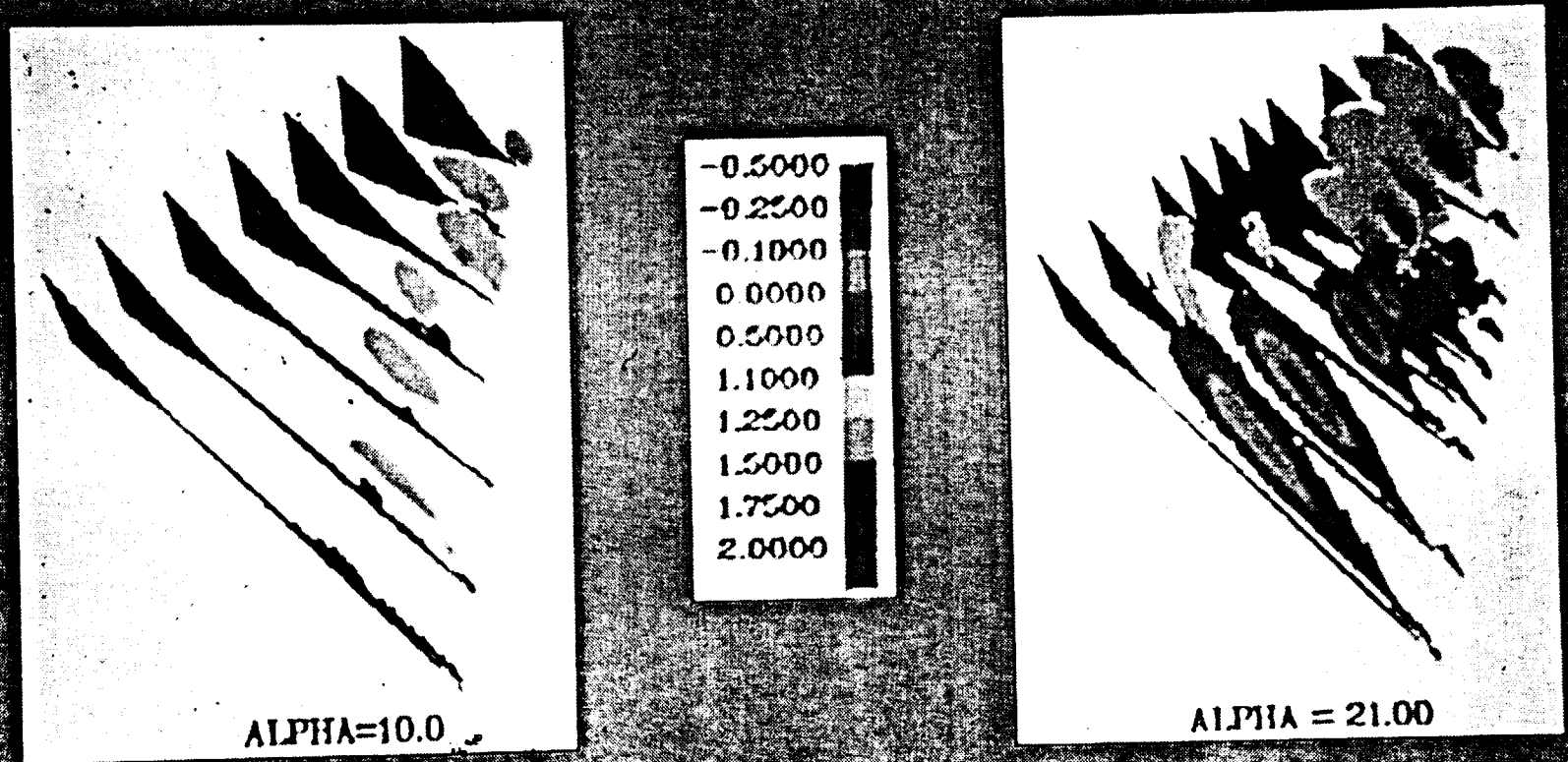
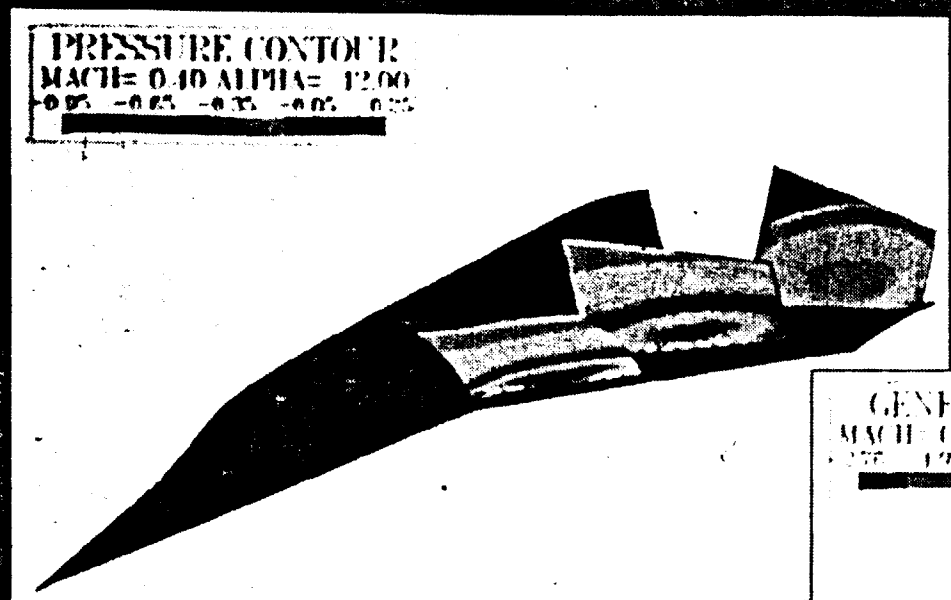


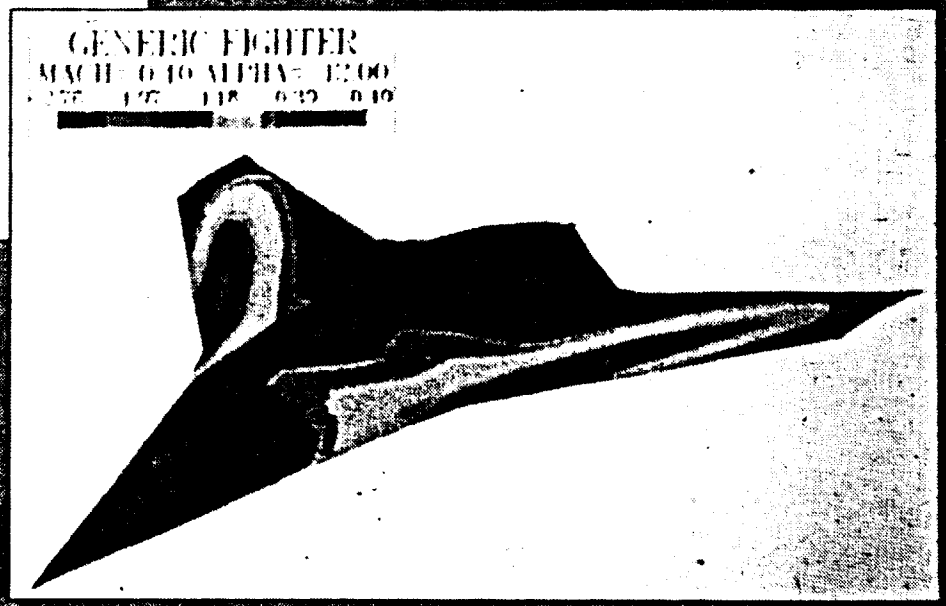
Advanced Fighter Code Validation Studies
Velocity Contours (LV Data)



7138-14

Advanced Fighter Investigations
3-D Navier-Stokes Analyses





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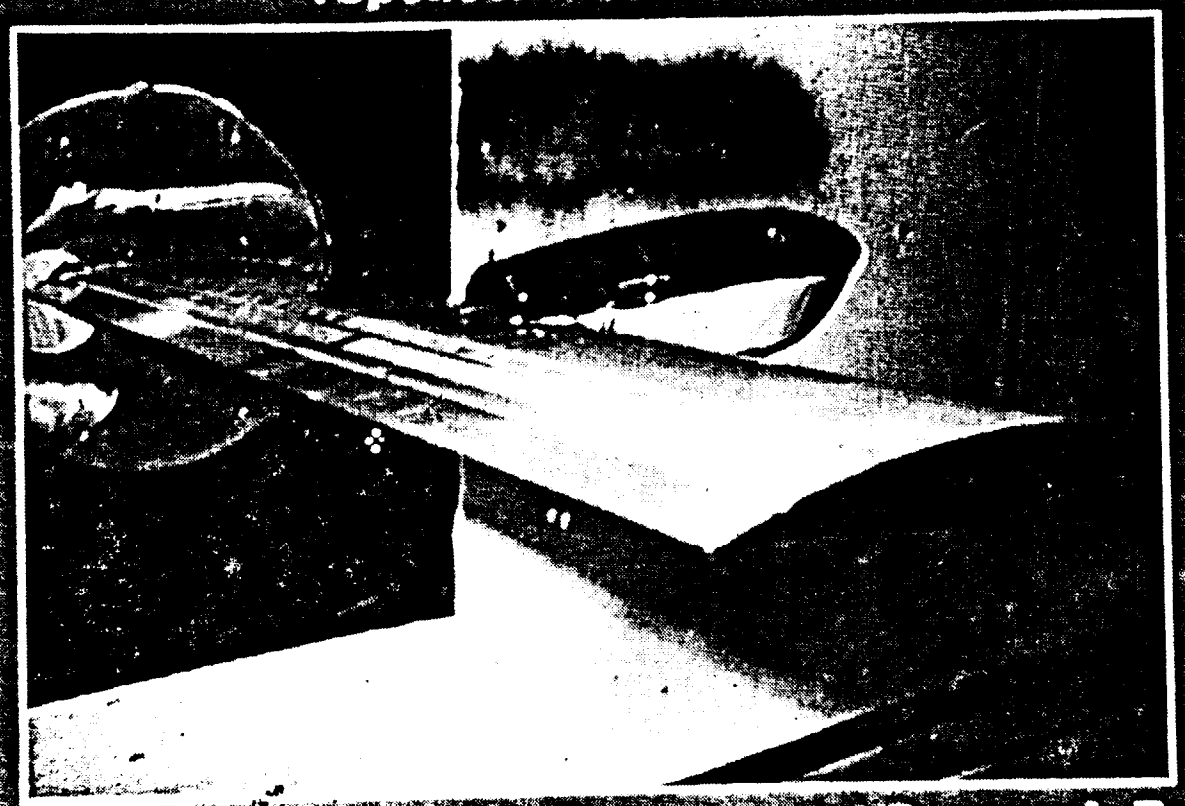
Laser Velocimeter Surveys of Upper Surface Blown Model

(Sponsor: Lockheed IRAD)



USB Configuration Mounted in Experimental Research Facility

AA-7284-18

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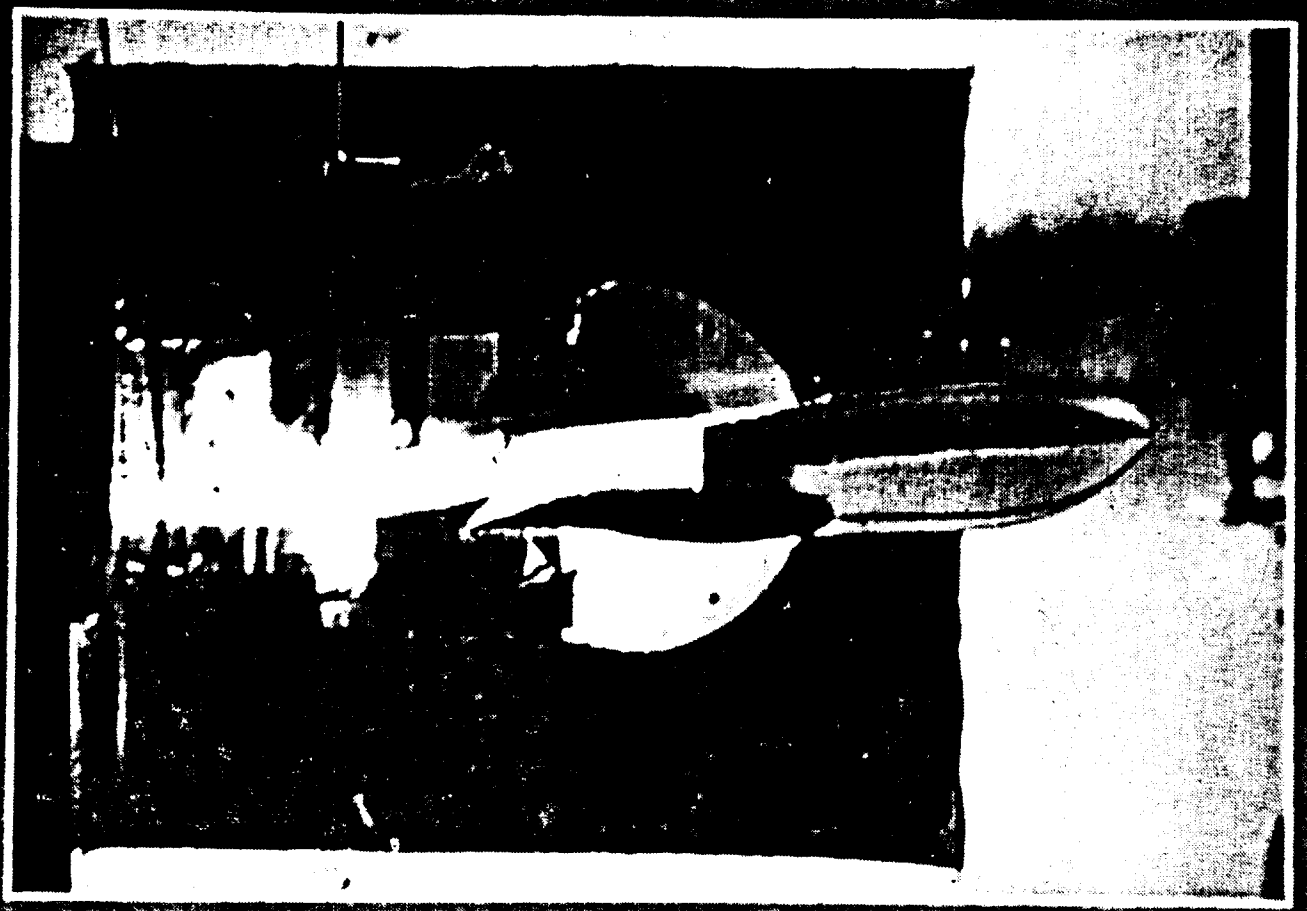
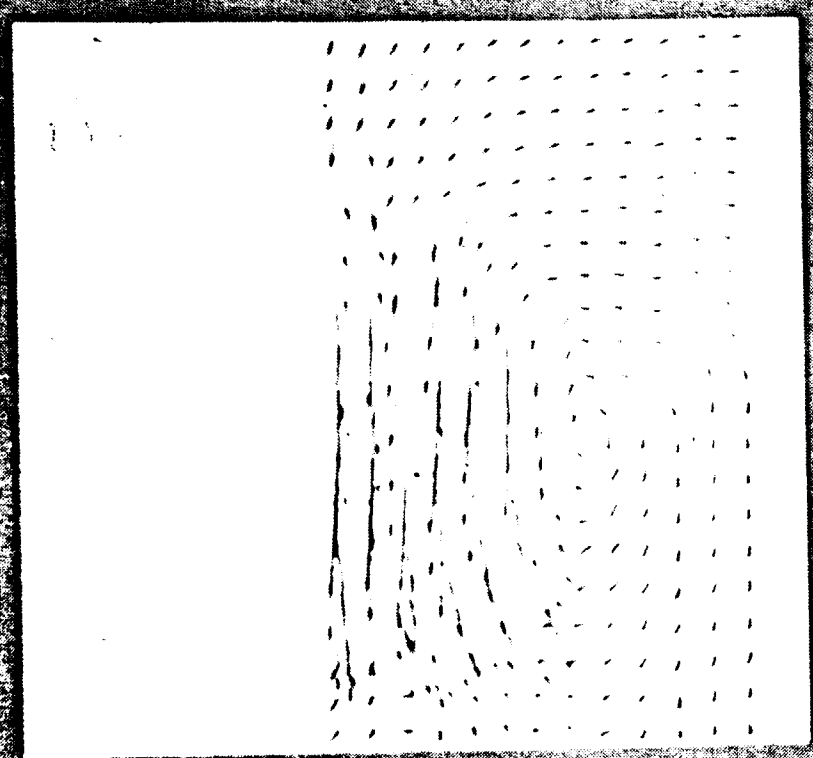
USB Jet Exhaust Illuminated With Laser Sheet Lighting

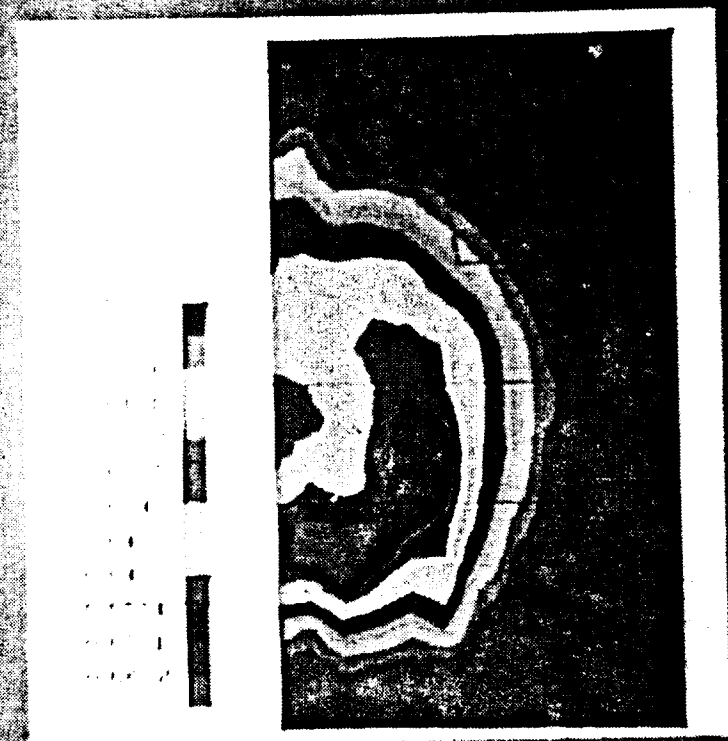


QA-7254-17

LV Measurements and Data Reduction of USB Jet Flowfield



Measured Velocity Vectors in the Cross Flow Plane

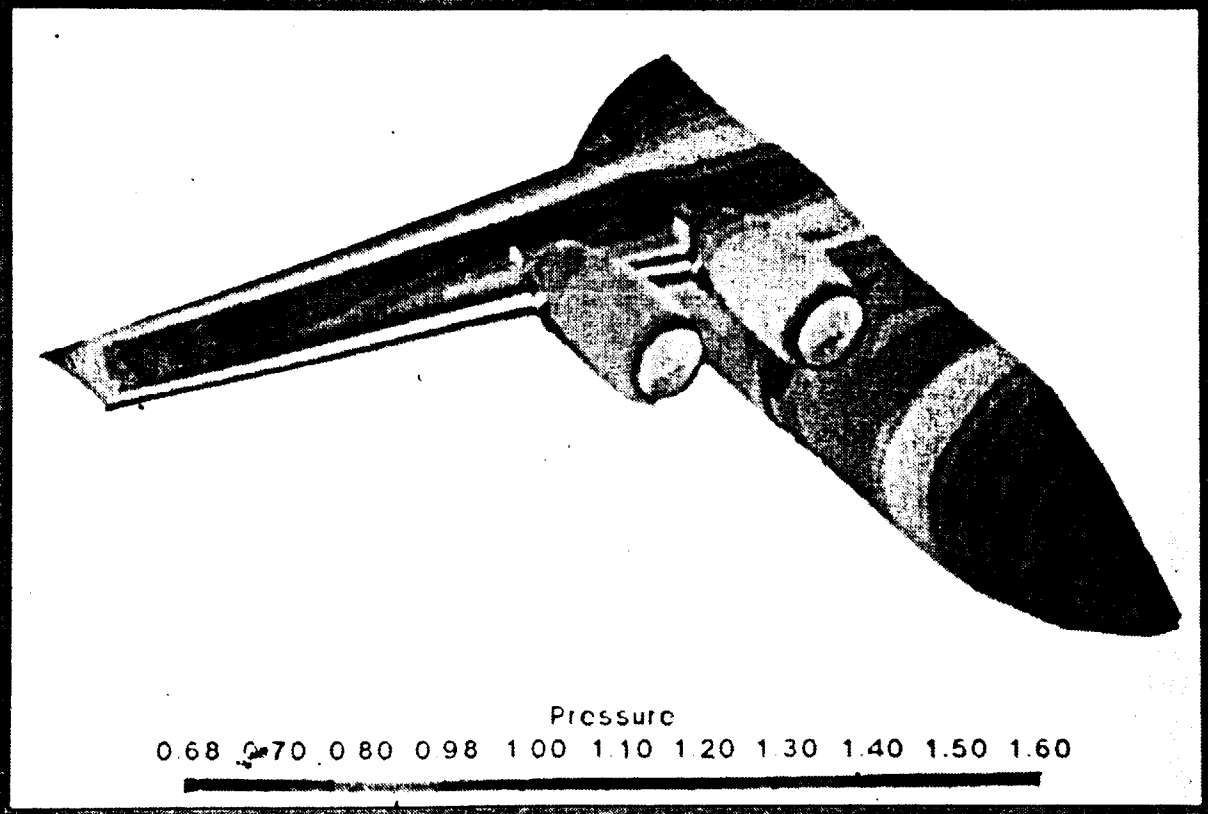


Contours of Turbulent Kinetic Energy

GA-7254-18

Over the Wing Blowing (OTW) Surface Pressures for Powered Lift

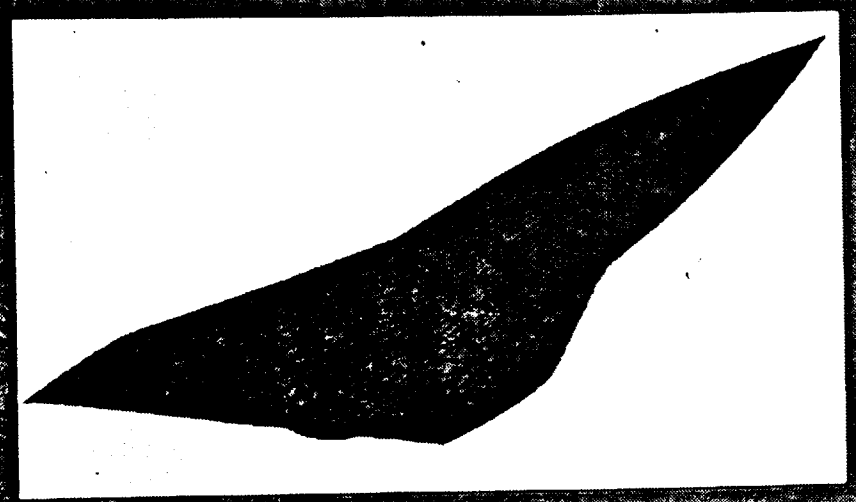
(Euler Analysis)



7136-10

Hypersonic Vehicle Studies
Lockheed-Georgia IRAD Support

Hypersonic Vehicle Grid

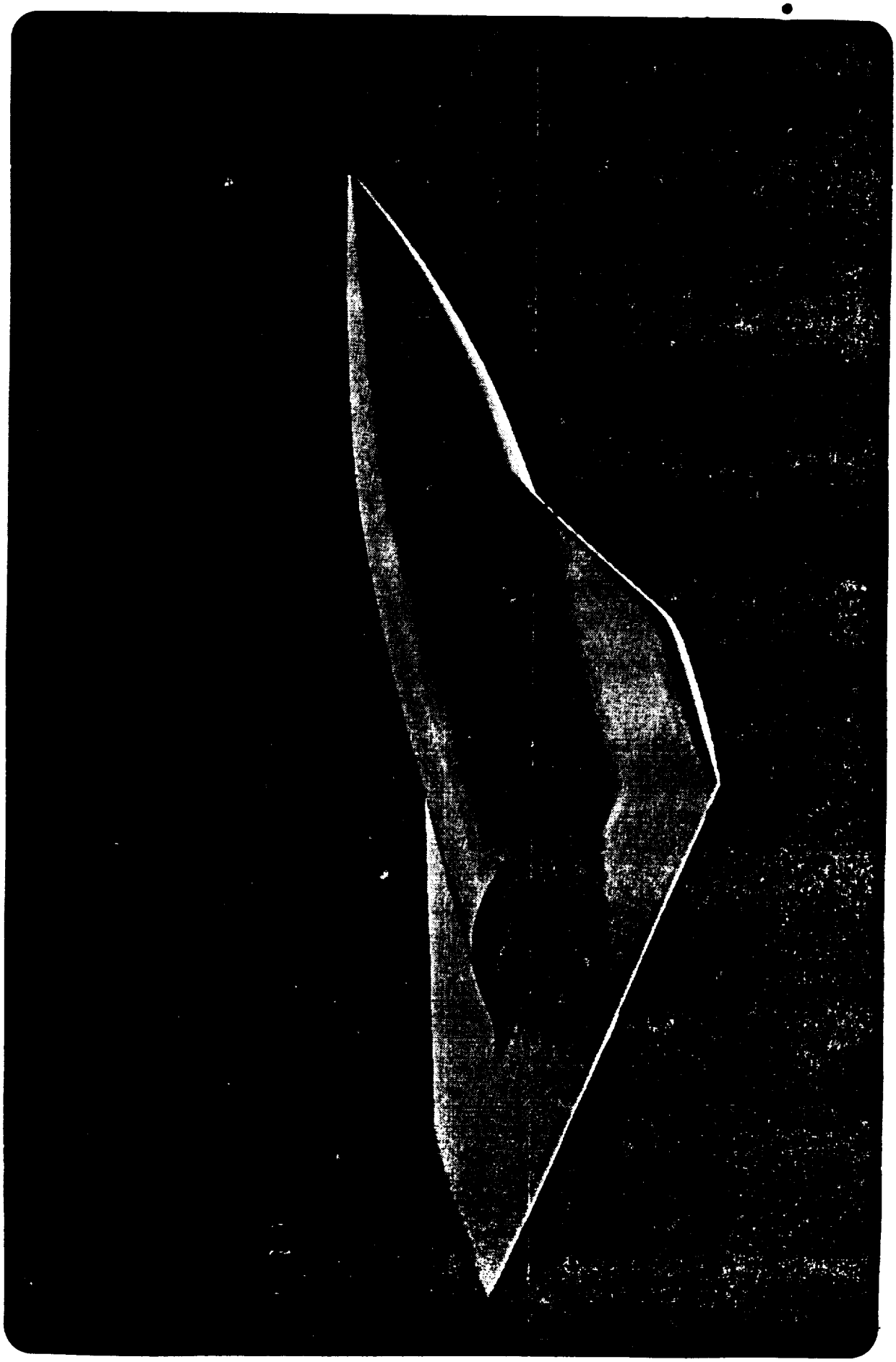


1986 - Transonic Base-Flow Investigations

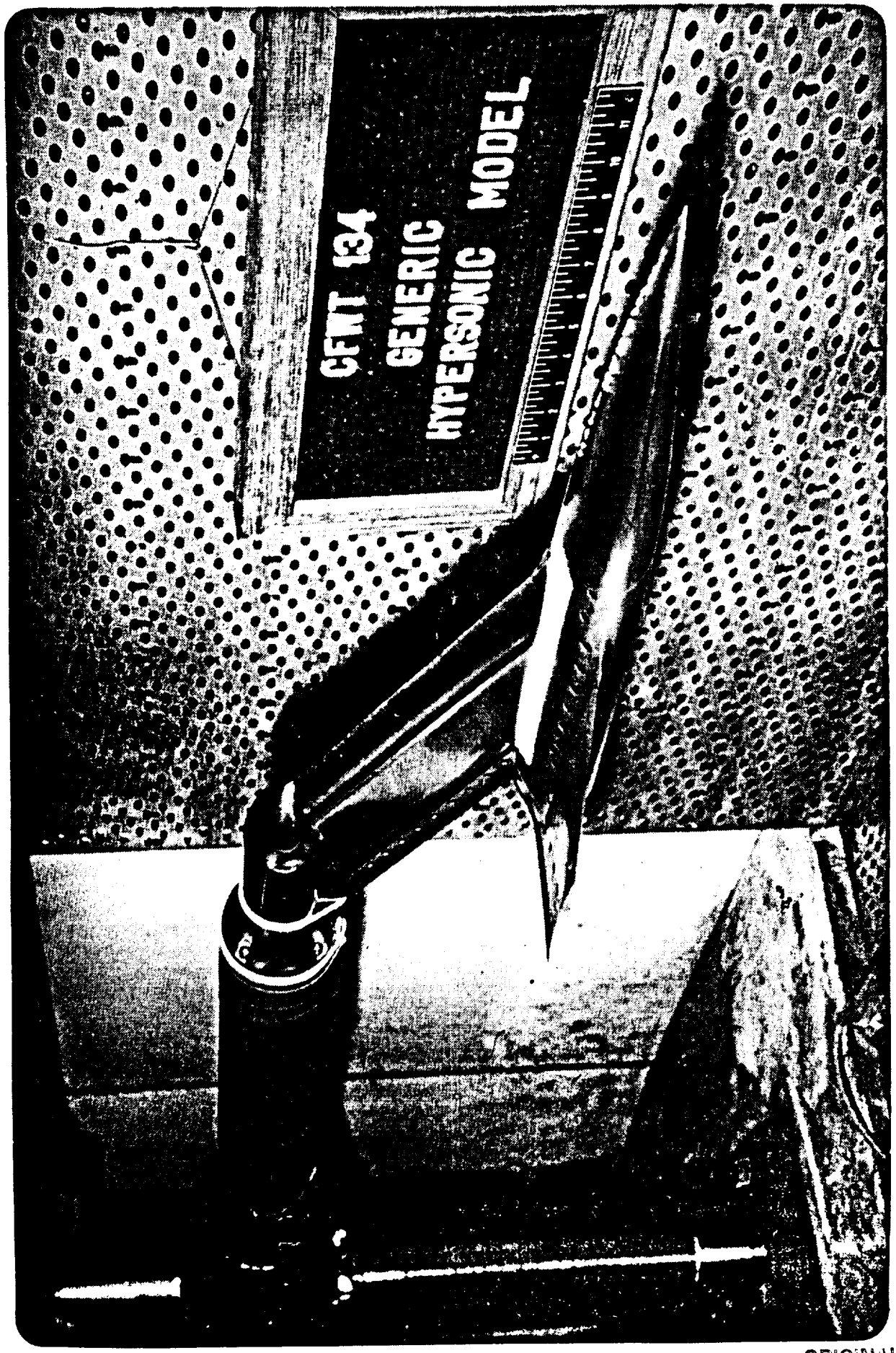
1987 - Subsonic Studies

1988 - Hypersonic Evaluations

7130-17



526



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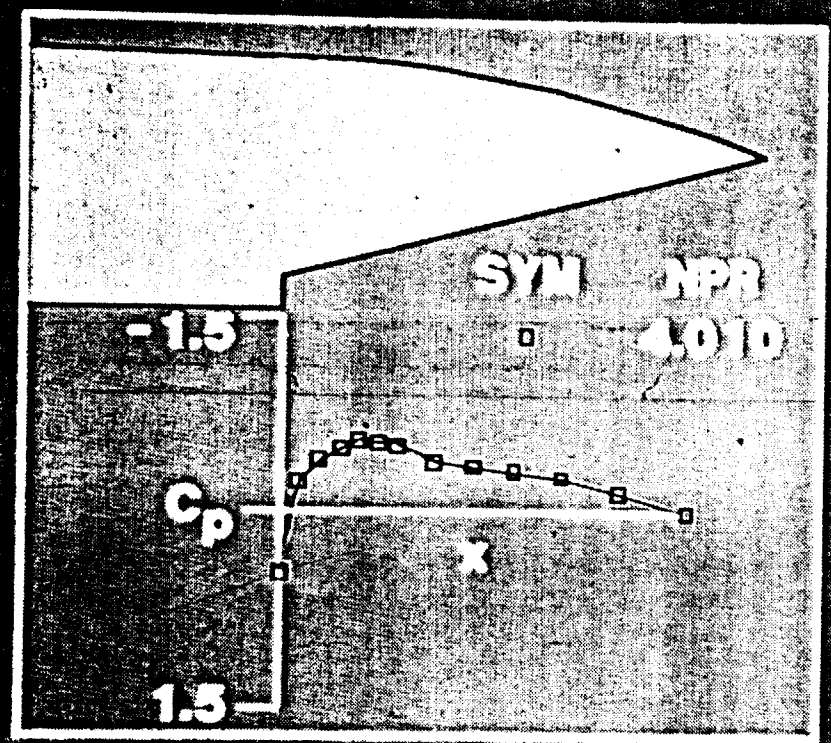
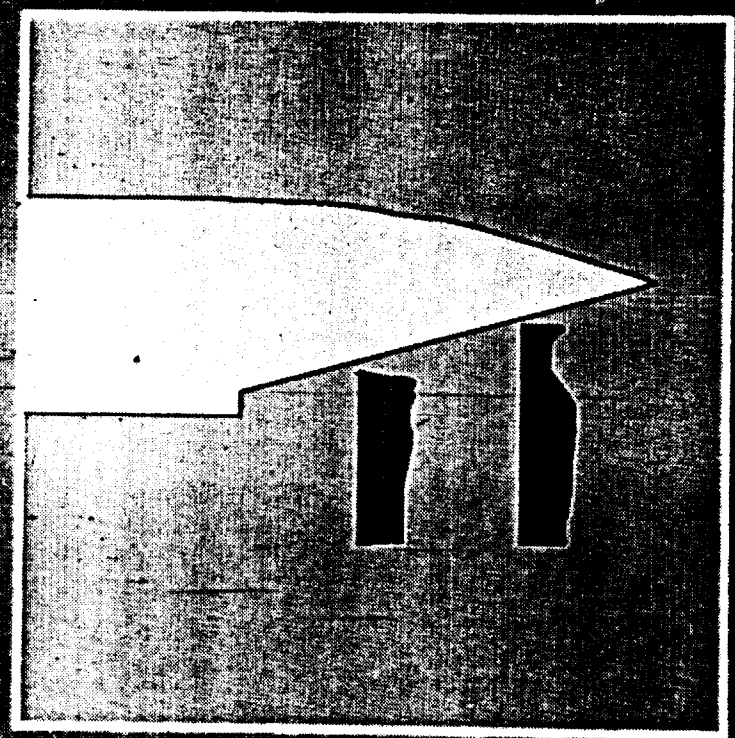
Hypersonic Vehicle - High Speed Test

$M_\infty = 1.46$
NPR = 4.0



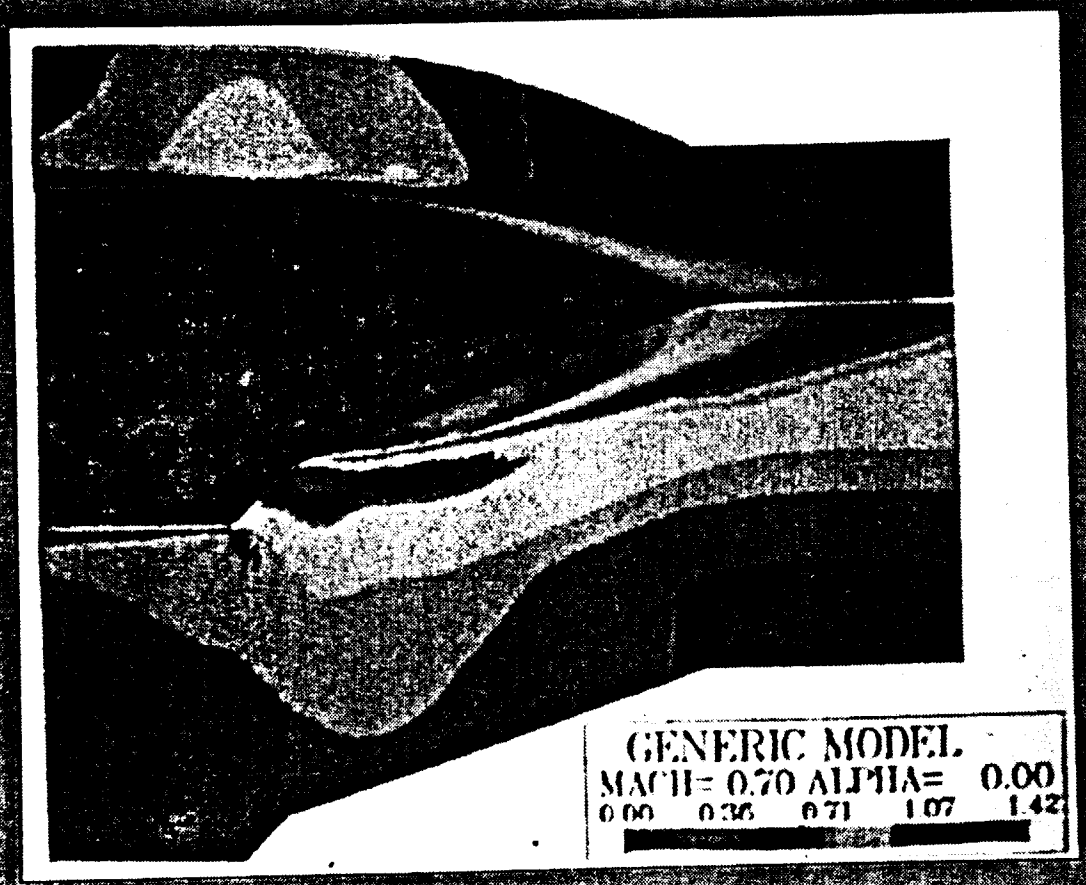
Afterbody Pressures



Mach Number Distributions

GA-7254-20

Transonic Base Flow of Hypersonic Vehicle
3-D Navier-Stokes



7138-19

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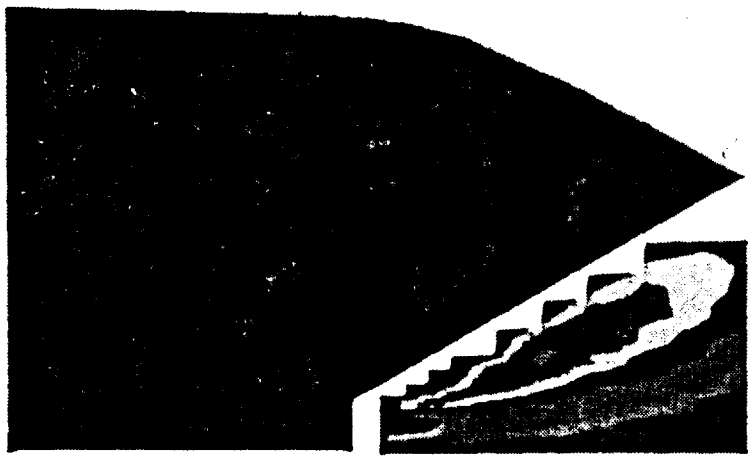
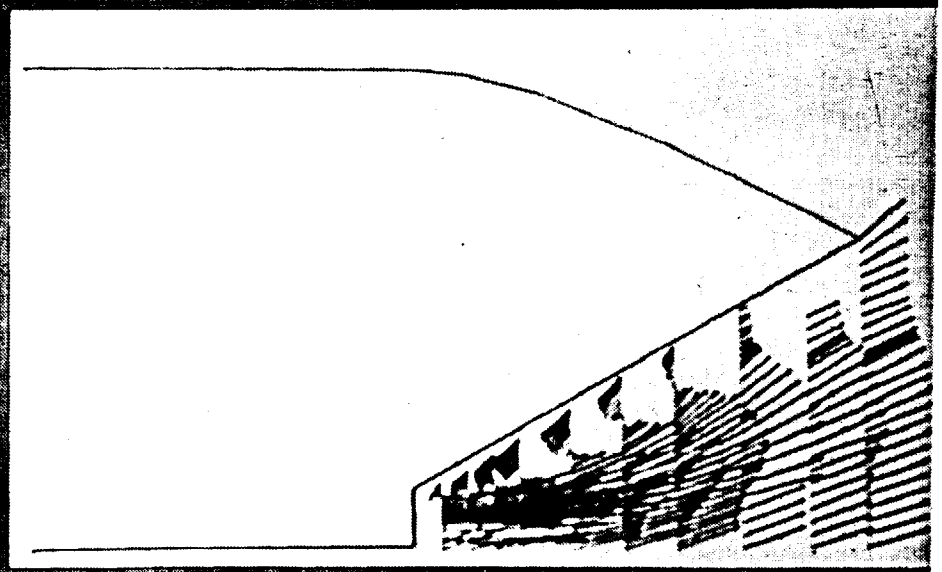
Hypersonic Vehicle - Low Speed Flowfield LV Surveys

Turbulence

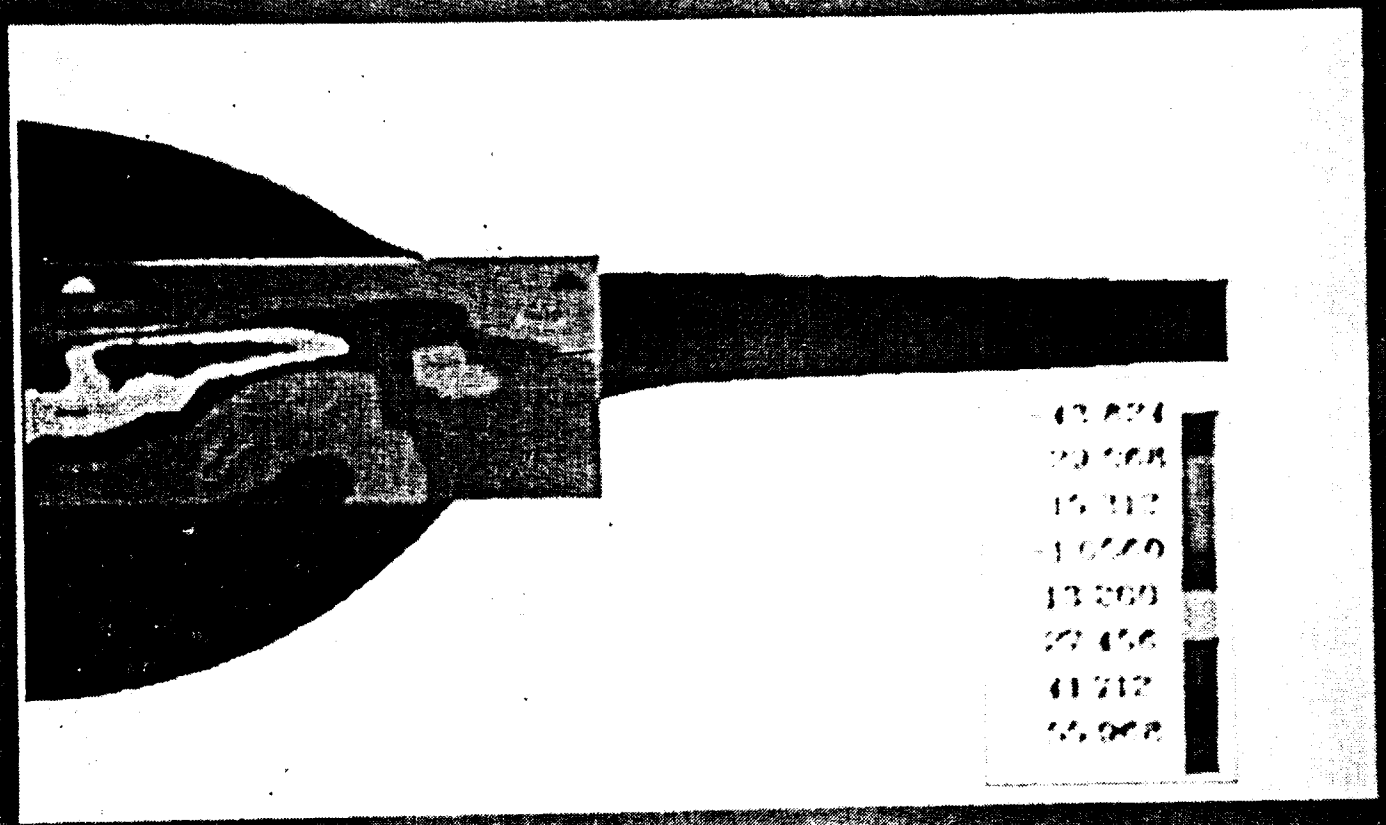


Mean Flow



7138-18

Hypersonic Vehicle - Low Speed Flowfield LV Surveys



Contours of Streamwise Vorticity in the Cross Flow Plane

GA-7284-19

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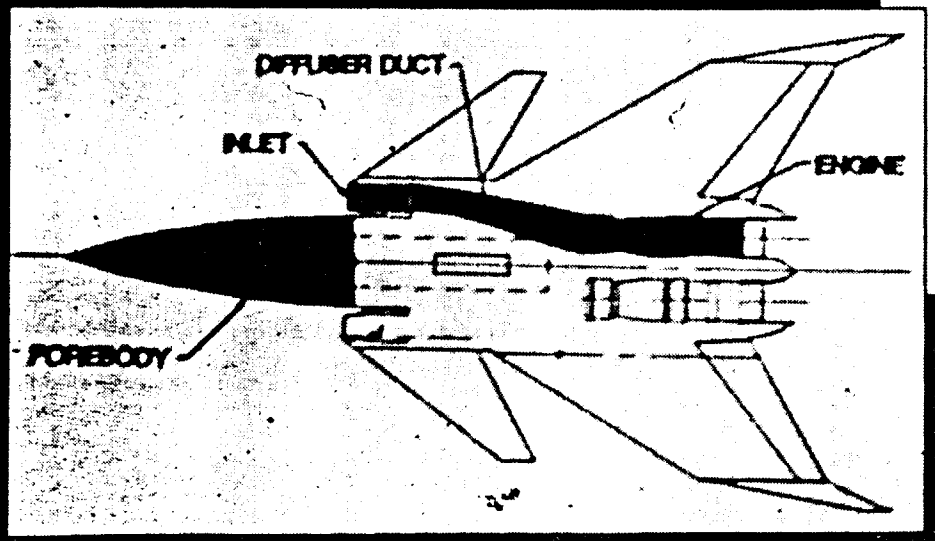
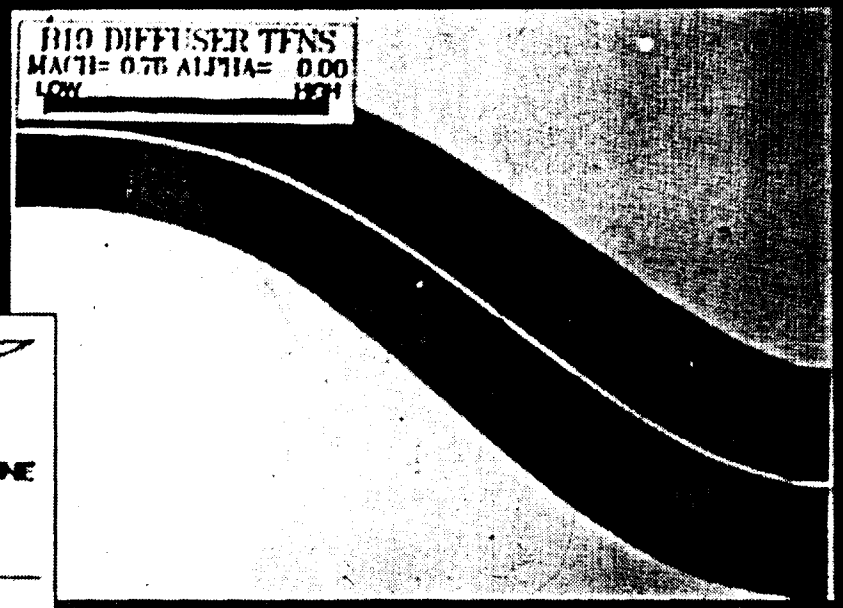
Propulsion Systems
Diffuser Duct Analysis

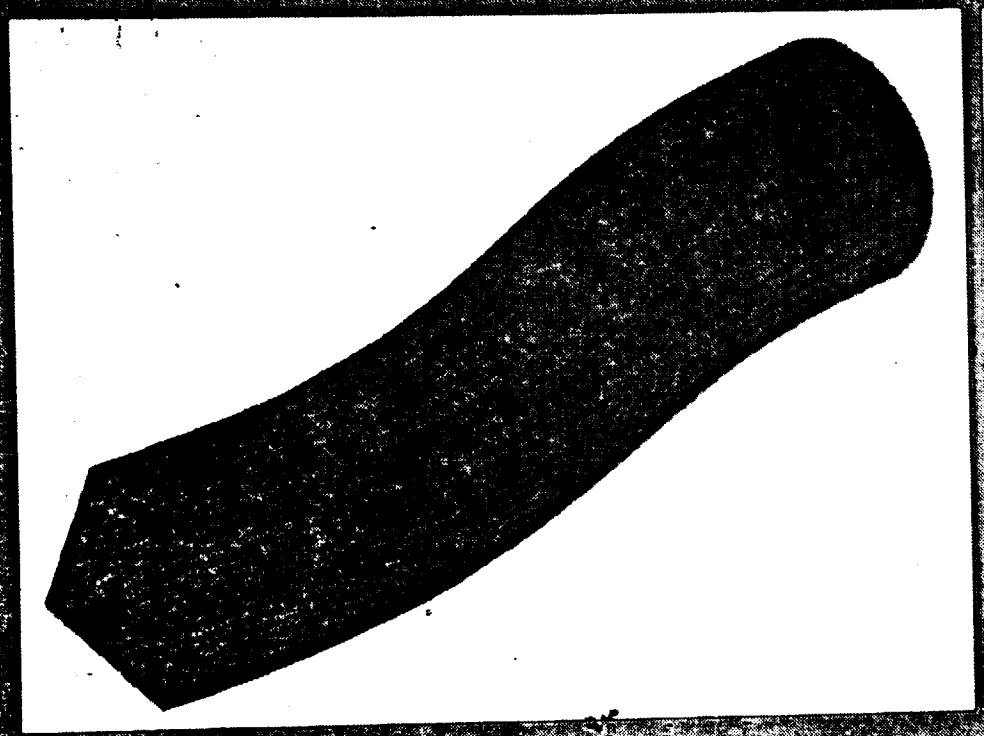




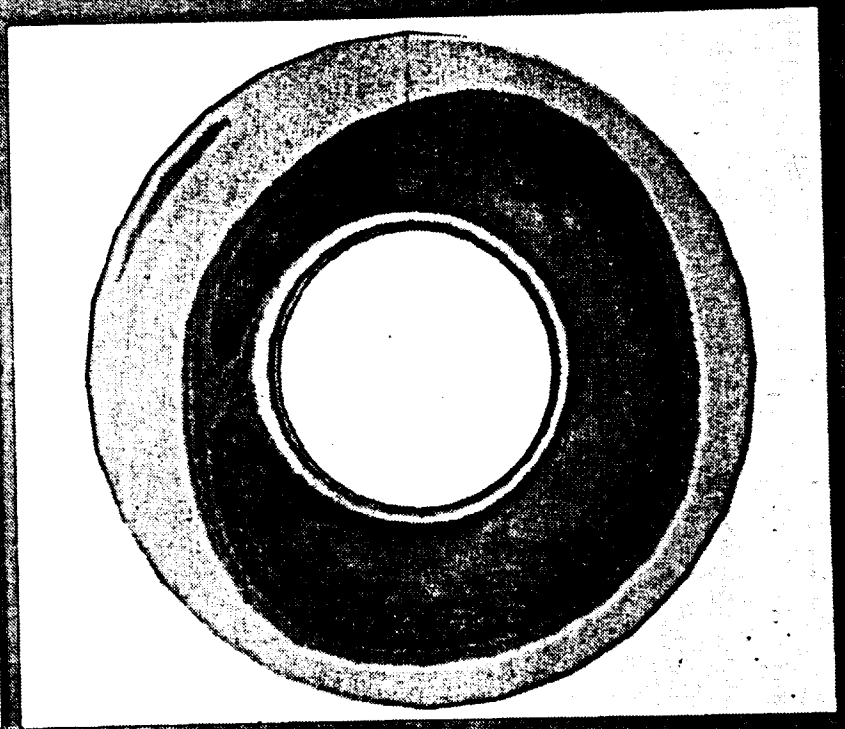
7138-15

Diffuser Duct Flow Distortion
3-D Navier-Stokes

Surface Grid

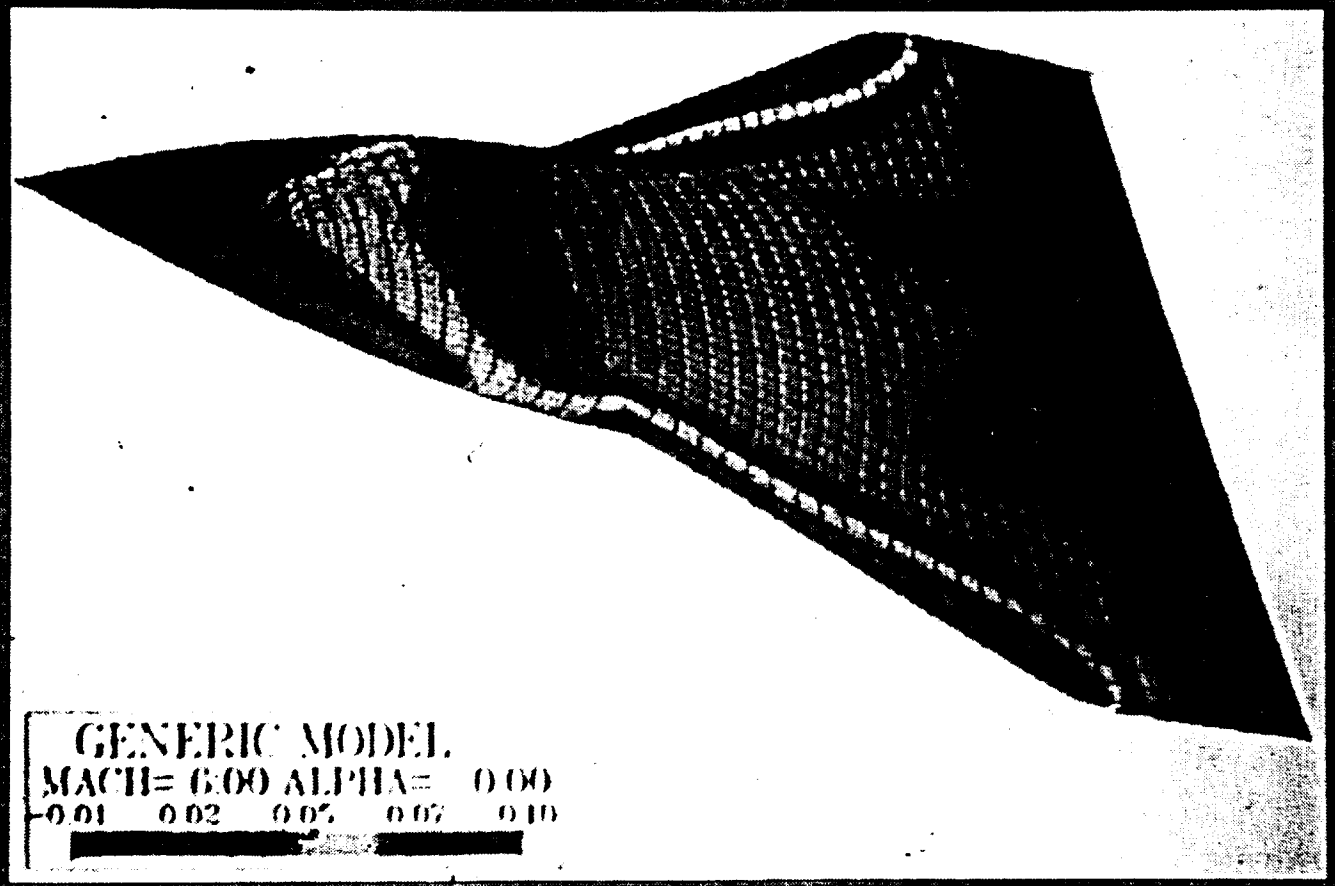


Mach Contours at Compressor Face



7136-10

Hypersonic Flowfield Computations
3-D Navier-Stokes



7138-20

Summary

Significant Accomplishments in Developing Code-Correlation Databases for a Variety of 2-D and 3-D Configurations

Further Research Requirements

- Complete Configurations
- Powered Configurations
- Vortical and Separated Flow Conditions
- High-Speed Flowfield Diagnostic Techniques
- High-Speed Databases
- Turbulence Modeling Data

GA-7254-21

CFD Validation Experiments at McDonnell Aircraft Company

N92-70944

22

A. Verhoff
MCDONNELL AIRCRAFT COMPANY

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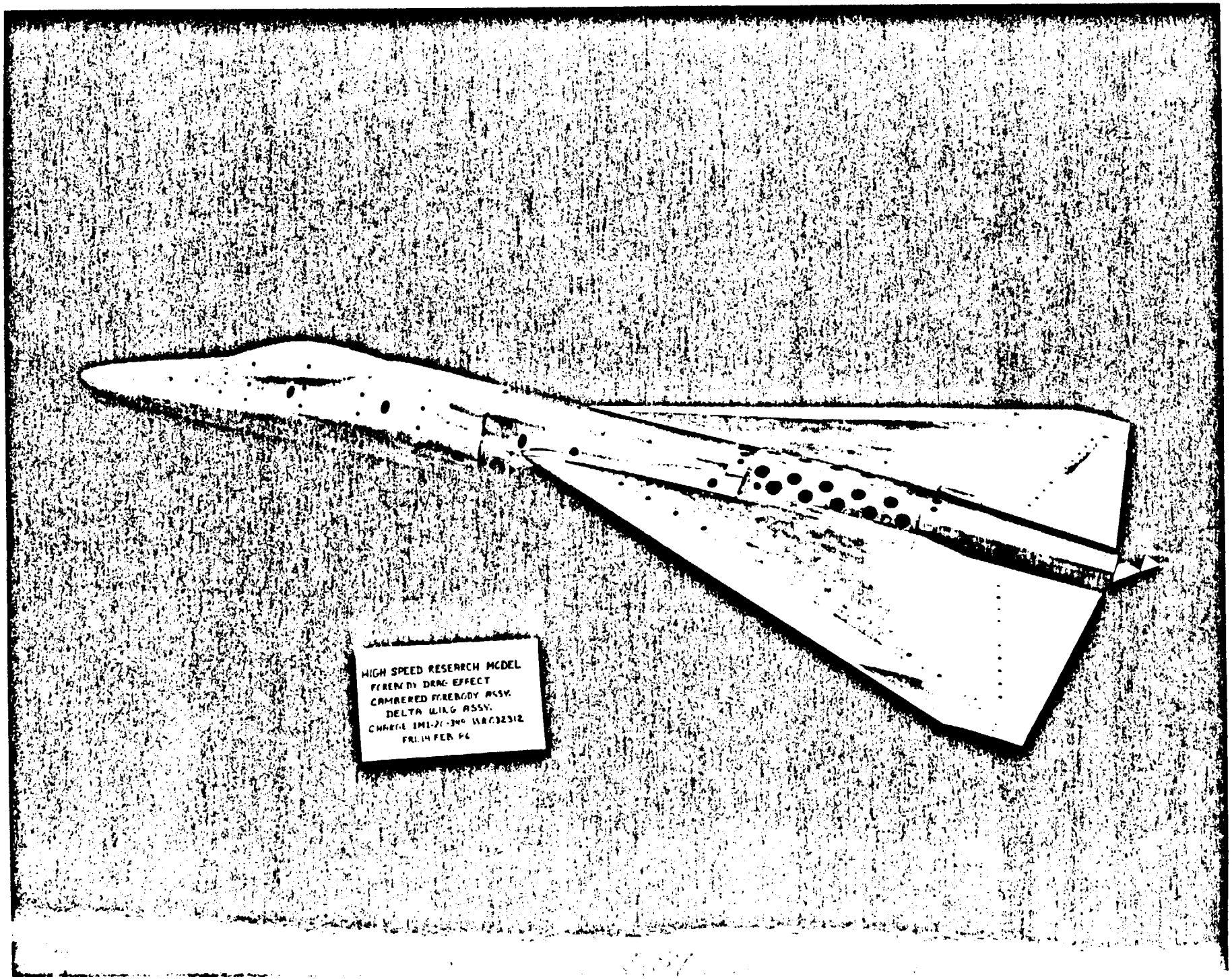
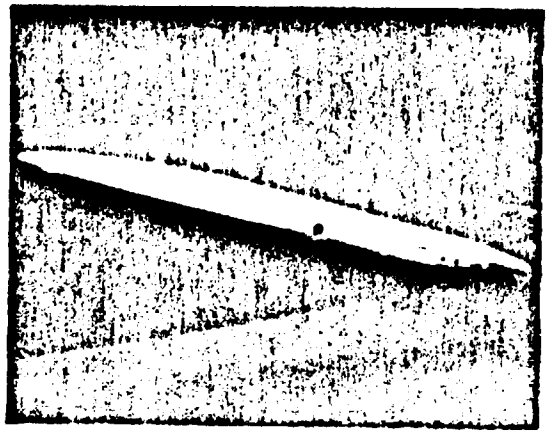
VALIDATION ACTIVITIES

- High Speed Research Model (HSRM)
- Supersonic Persistence Fighter Model (SSPF)
- Generic Fighter Wing Model
- NASP Option II Models
  - Blended Wing Body
  - Caret
  - Inlet
  - Nozzle

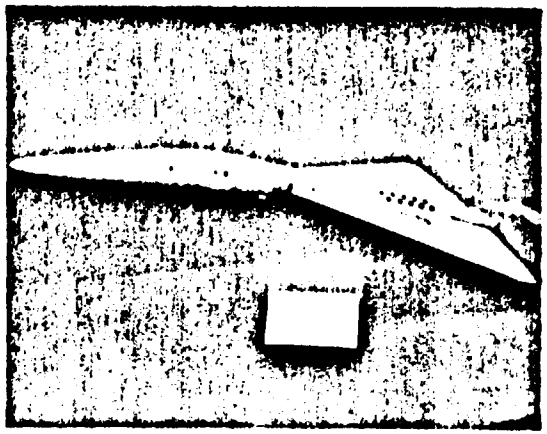

HIGH SPEED RESEARCH MODEL
FOREBODY DRAG EFFECT
CAMBERED FOREBODY ASSY.
DELTA WING ASSY.
FRI 14 FEB 96

MCAIR HIGH SPEED RESEARCH MODEL CONFIGURATIONS

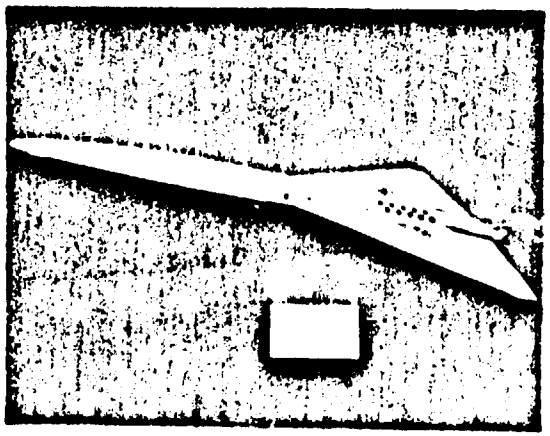
FOREBODY WAVE DRAG INVESTIGATION



UNCAMBERED FOREBODY (WING OFF)



CAMBERED FOREBODY (WING ON)



UNCAMBERED FOREBODY (WING ON)

CAMBERED FOREBODY WITH CANOPY (WING ON)

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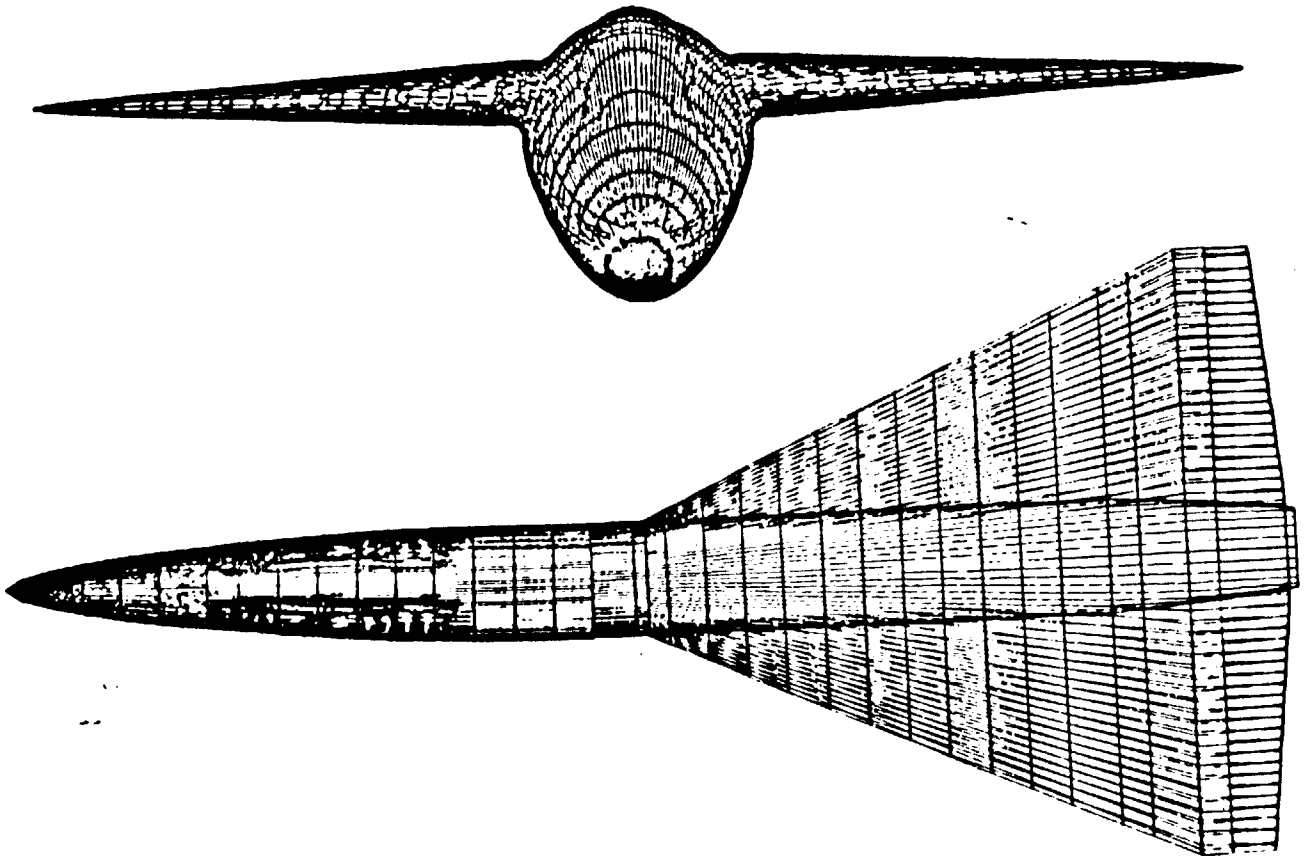
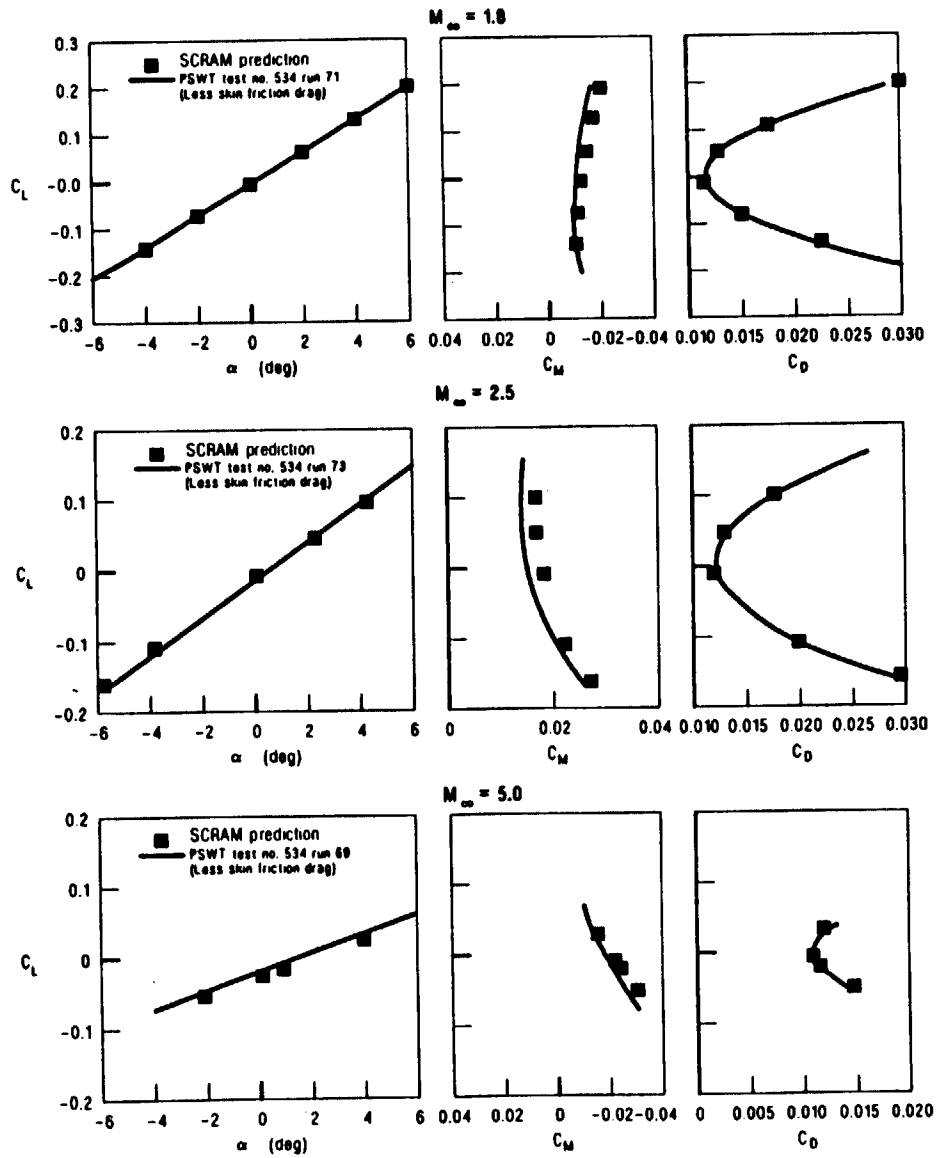
Surface Grid for High Speed Research Model



GP73-0173-16-R

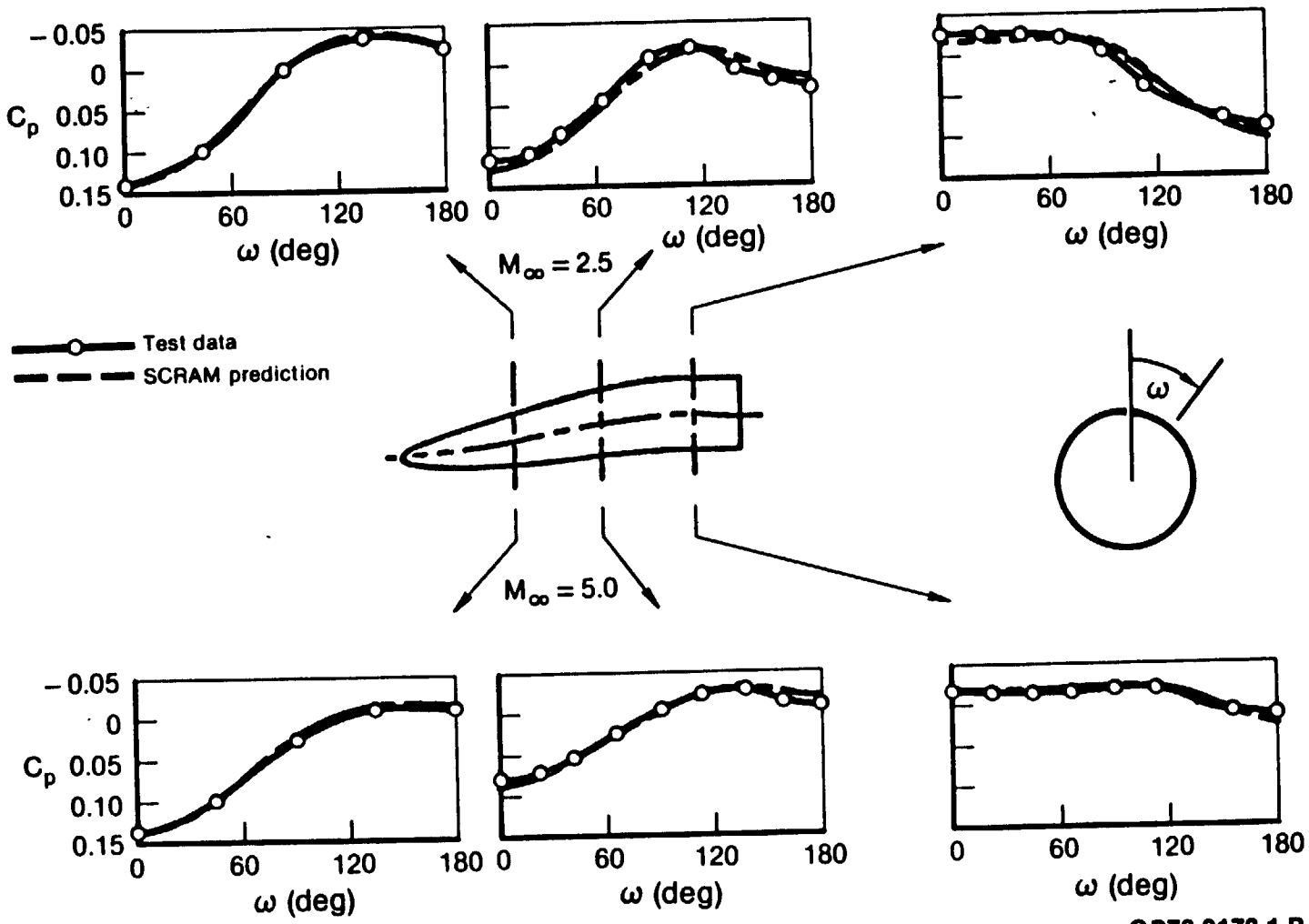
Force and Moment Predictions for High Speed Research Model



GP73-0173-14-R

Surface Pressure Predictions for Cambered Forebody (Canopy Off)

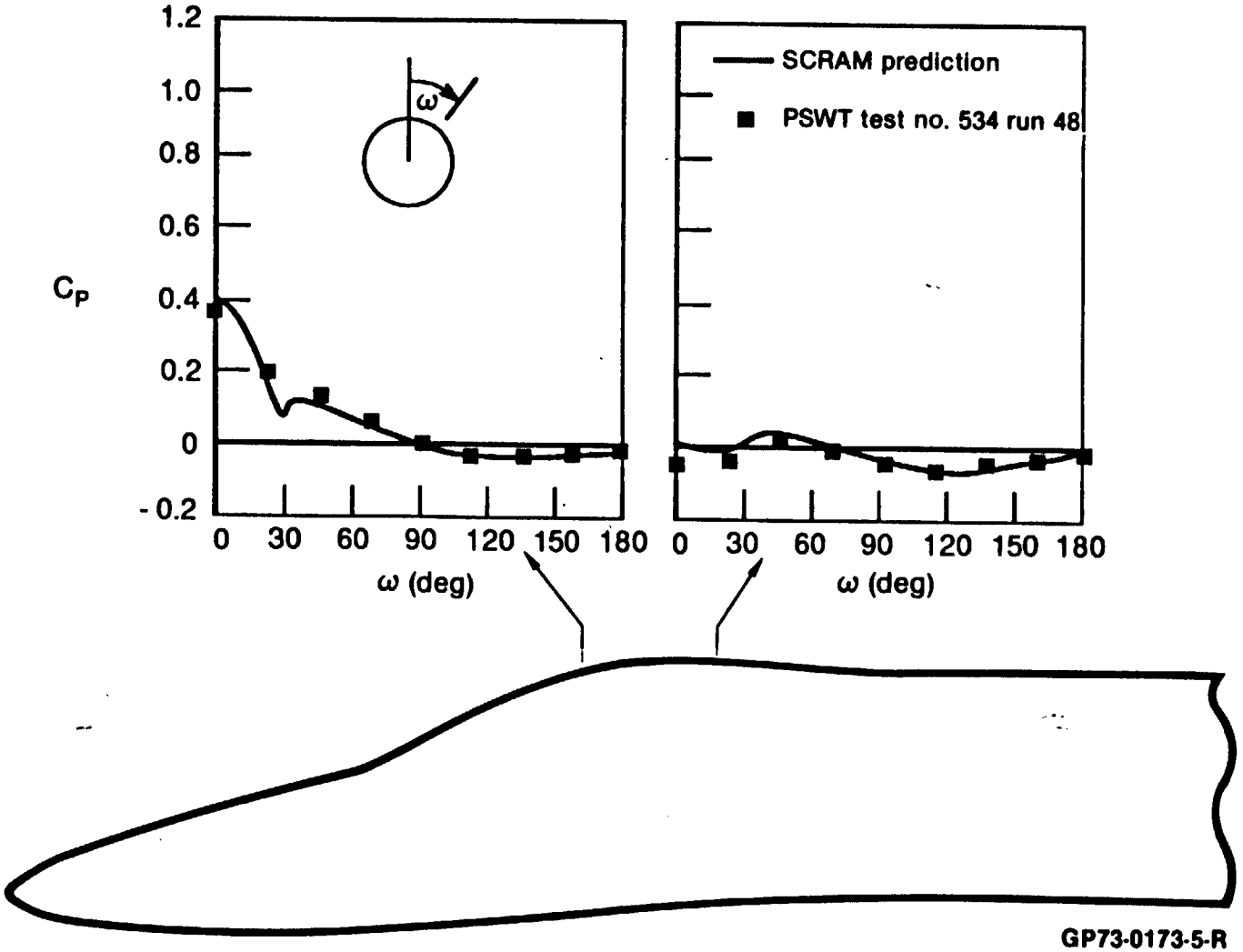
$\alpha = 0°$



GP73-0173-1-R

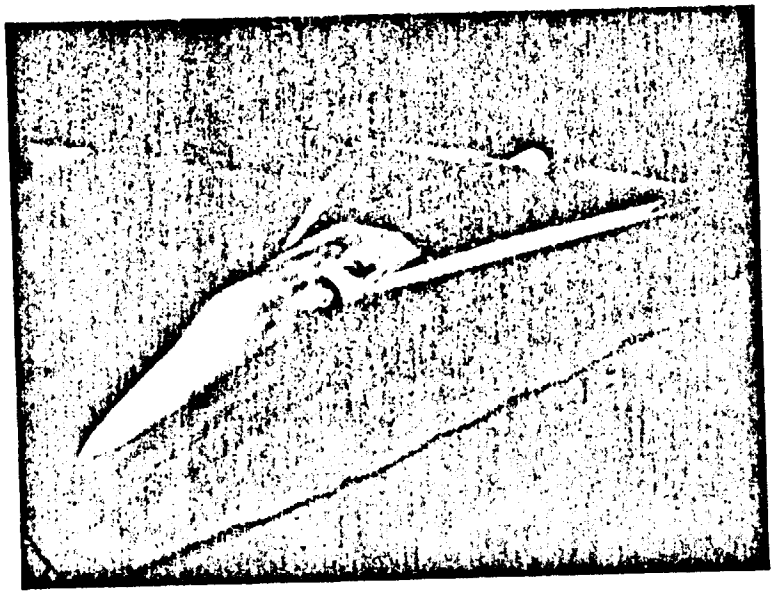
Surface Pressure Predictions for Cambered Forebody (Canopy On)

$M_\infty = 2.5;\ \alpha = 0°$

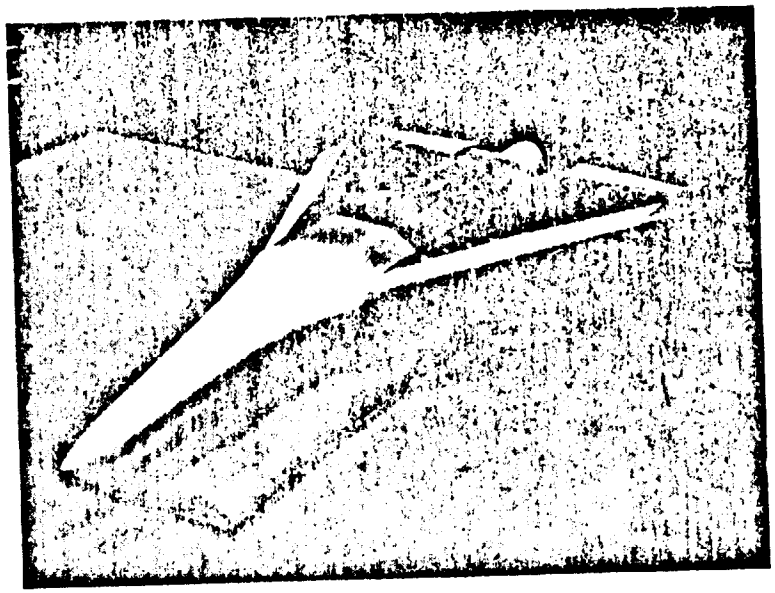


GP73-0173-5-R

4% SCALE SSPF FOREBODY MODELS WITH 65° CLIPPED DELTA WING



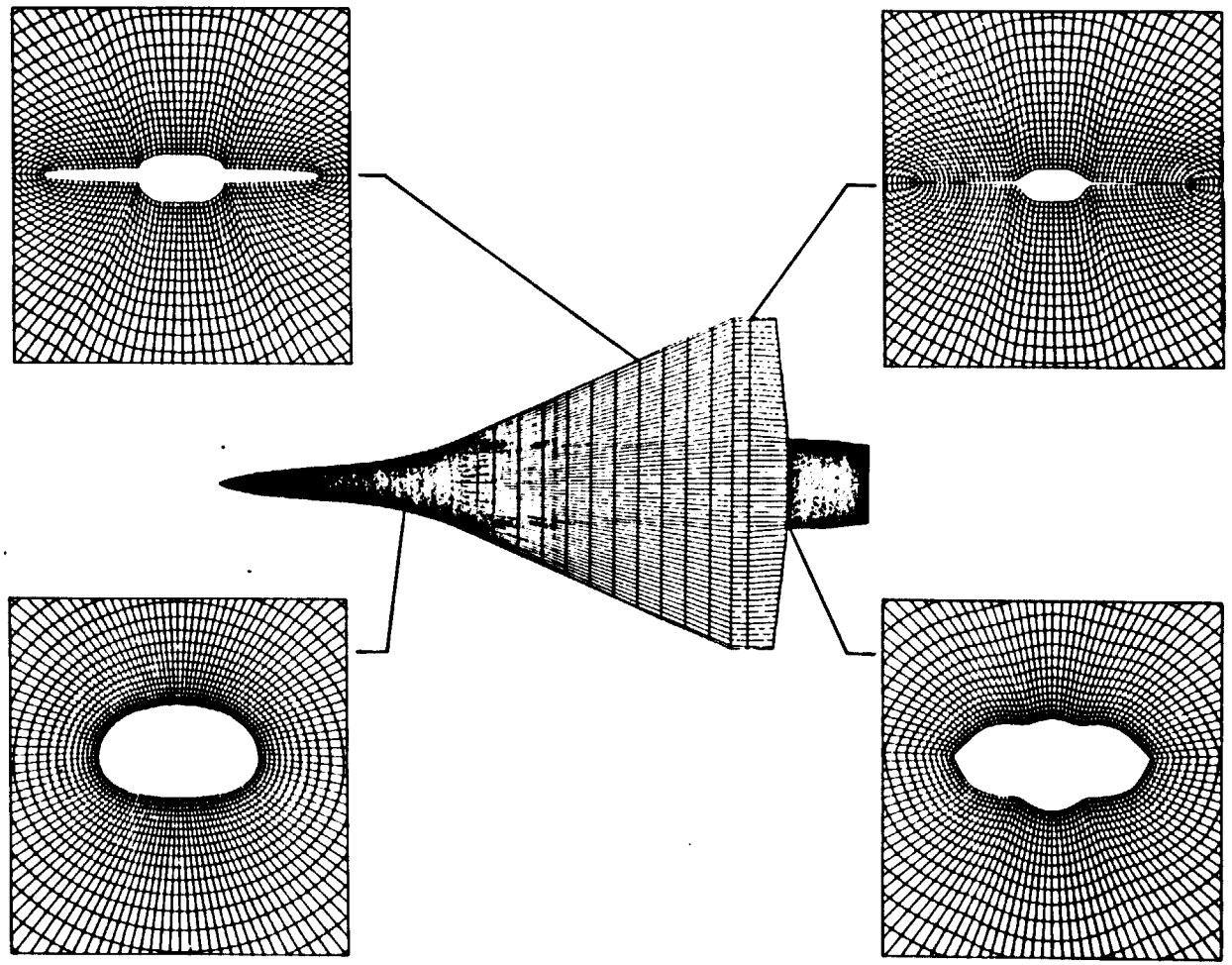
ORIGINAL FOREBODY
WITH INLETS
(NON-INSTRUMENTED)



CAMBERED, EQUIVALENT
FOREBODY WITH
FAIRED-OVER INLETS
(28 FOREBODY STATIC
PRESSURE TAPS)

GP83-0007-97-C

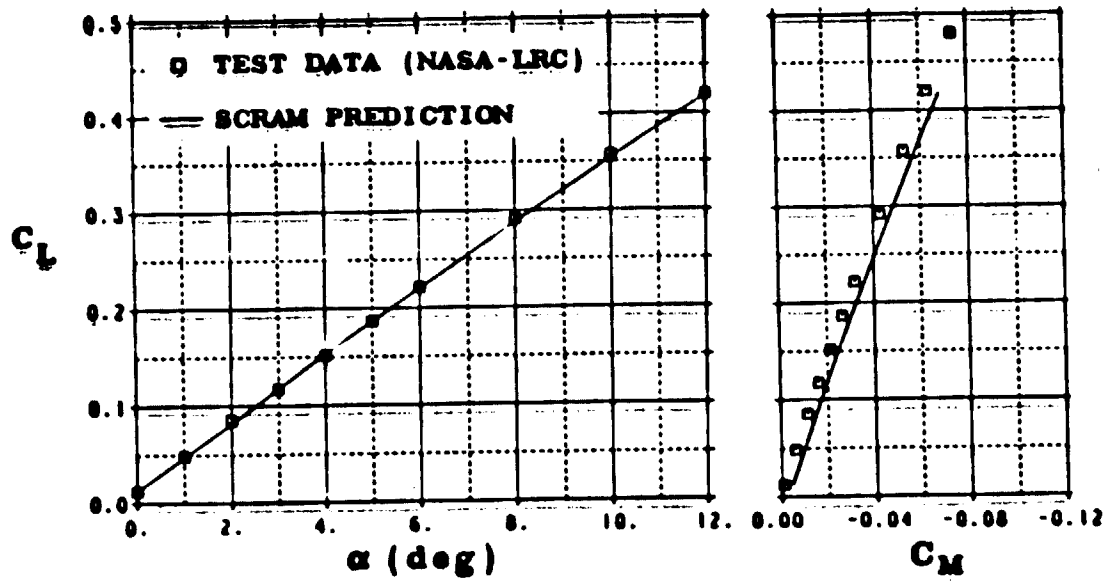
SCRAM Grid On SSPF Configuration

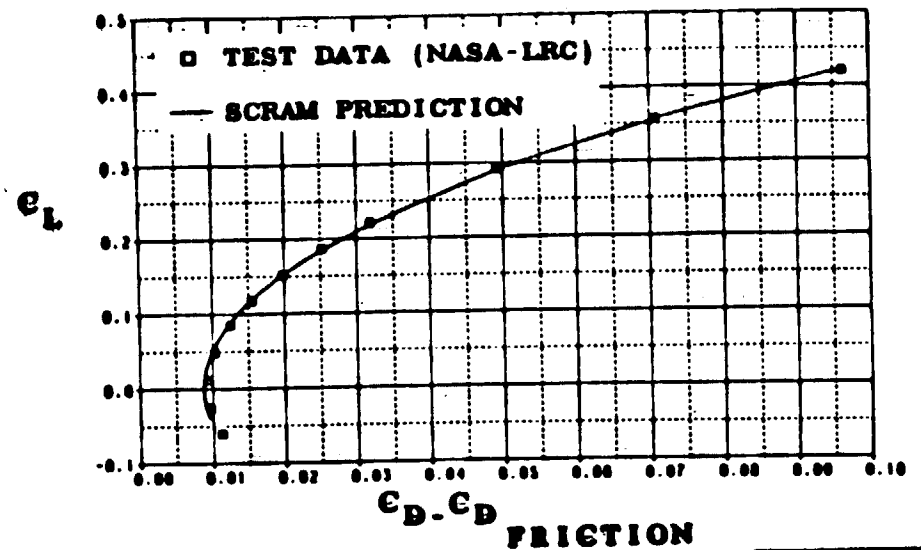


GP73-0280-77
MM-705

UNCAMBERED DELTA WING - 65° SWEEP

$M_\infty = 1.8$





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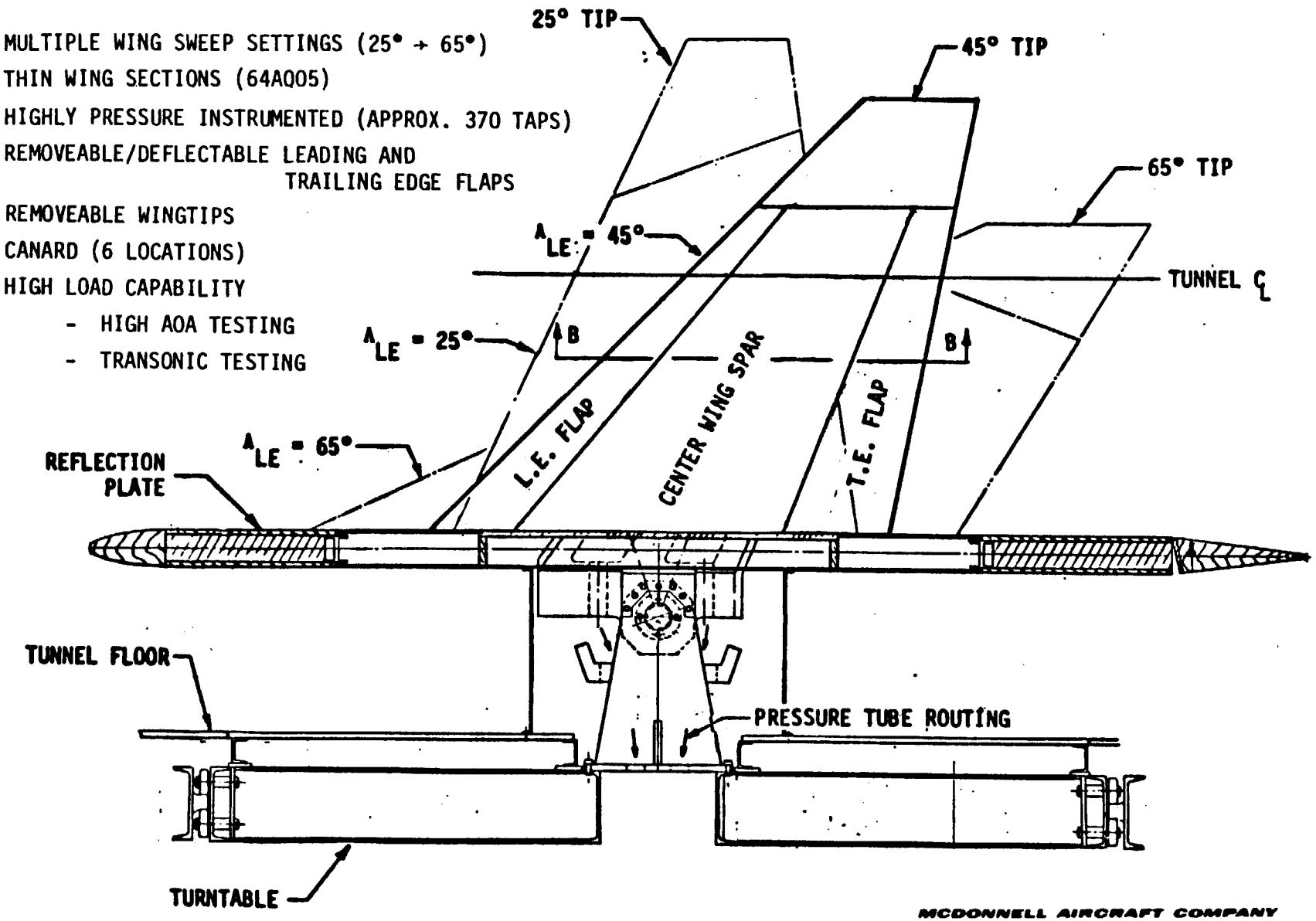
GENERIC RESEARCH WING INSTALLATION IN MCAIR LOW SPEED WIND TUNNEL

- o MULTIPLE WING SWEEP SETTINGS (25° → 65°)
- o THIN WING SECTIONS (64A005)
- o HIGHLY PRESSURE INSTRUMENTED (APPROX. 370 TAPS)
- o REMOVEABLE/DEFLECTABLE LEADING AND TRAILING EDGE FLAPS
- o REMOVEABLE WINGTIPS
- o CANARD (6 LOCATIONS)
- o HIGH LOAD CAPABILITY
  - HIGH AOA TESTING
  - TRANSONIC TESTING



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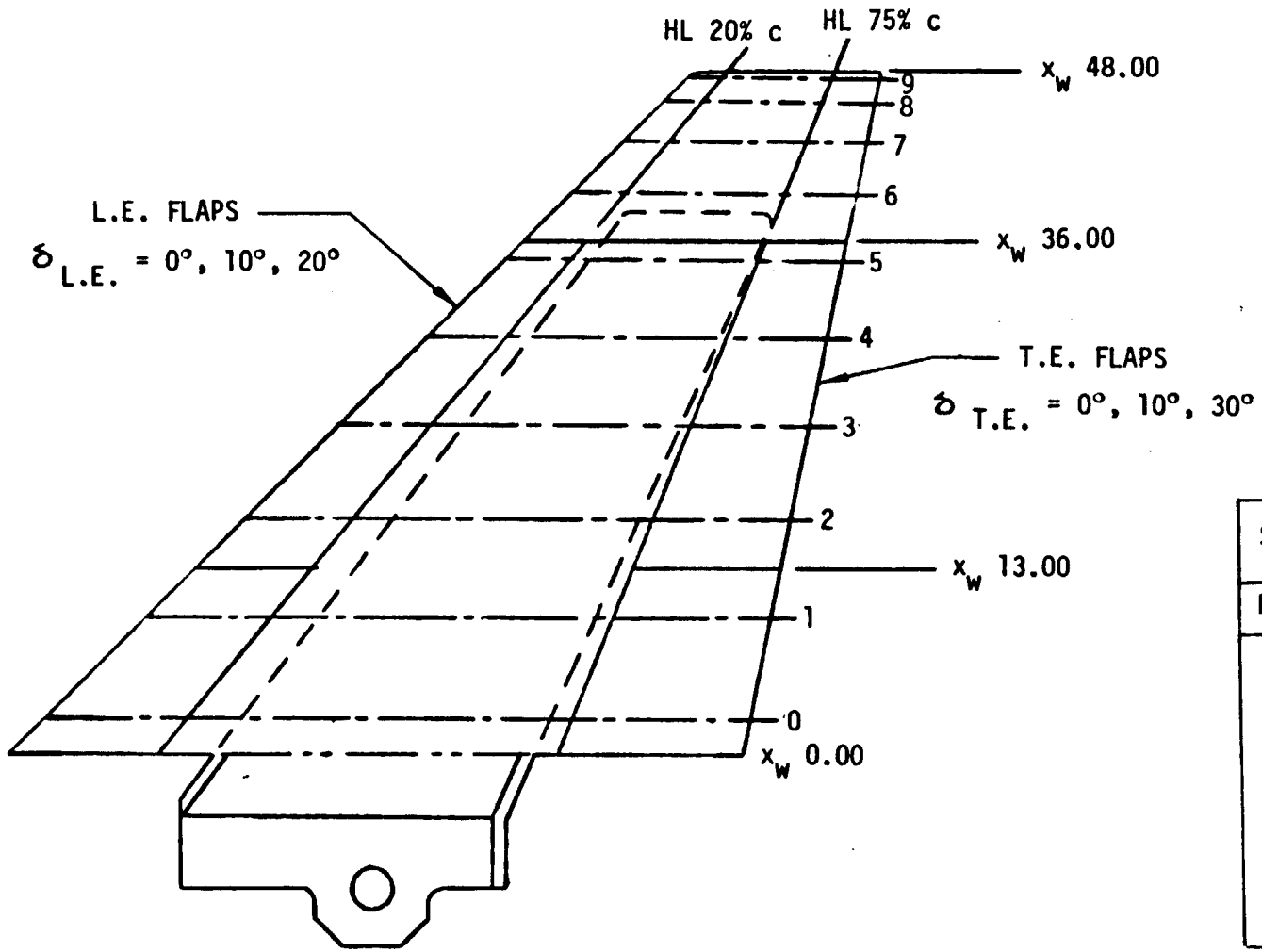
MCAIR GENERIC FIGHTER RESEARCH WING
45° L.E. SWEEP



WING CHARACTERISTICS	
$\Lambda_{L.E.}$	45°
λ	.25
b/2	48.00 in
C_R	51.20 in
C_T	12.80 in
AR	3.0
S/2	1536 in^2

STATIC PRESSURE ROW LOCATION	
ROW NO.	x_w
0	2.40
1	9.53
2	16.49
3	23.10
4	29.20
5	34.65
6	39.29
7	43.03
8	45.79
9	47.44

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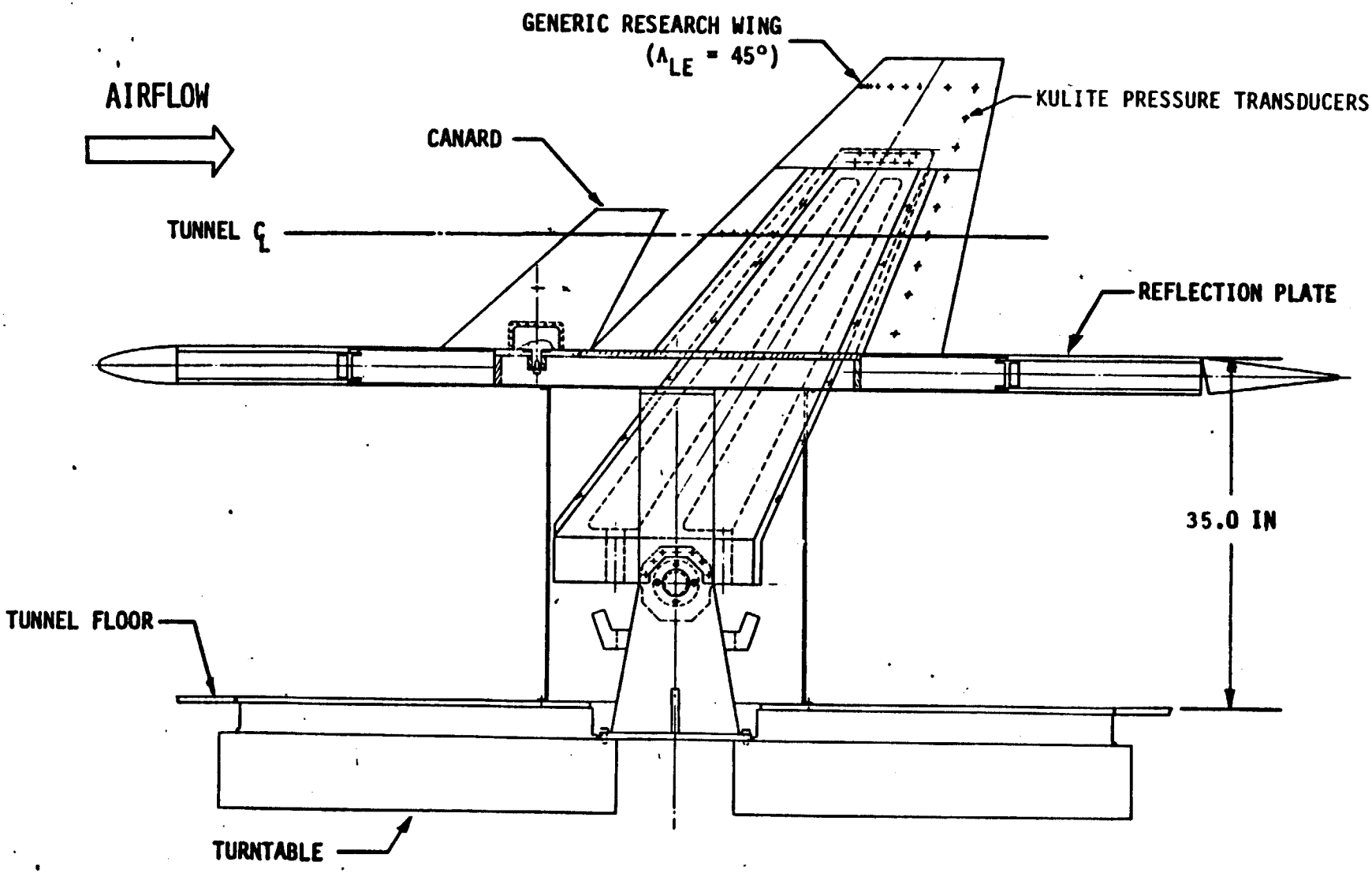
HORIZONTAL CANARD/WING CONFIGURATION
(MCAIR LOW SPEED WIND TUNNEL)



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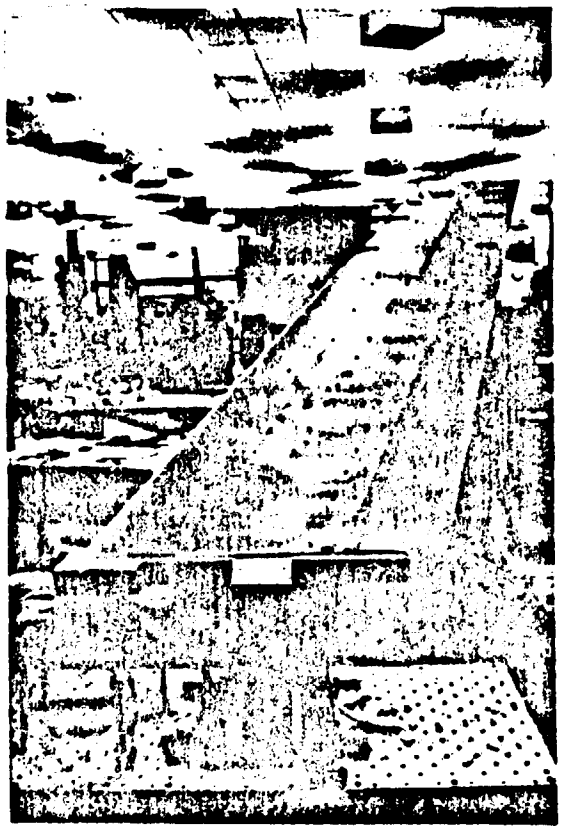
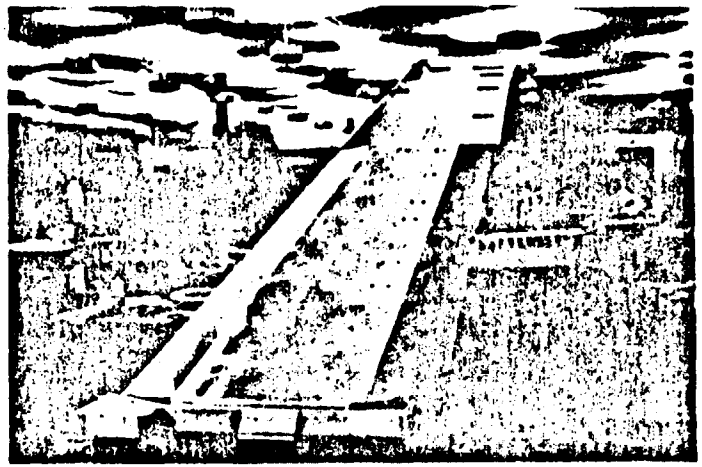
GENERIC FIGHTER WING MODEL

$\Lambda_{LE} = 45°$ CONFIGURATIONS



WITH SUPPORT STRUCTURE



WITH 20° LE, 30° TE FLAP DEFLECTIONS

WITH CANARD

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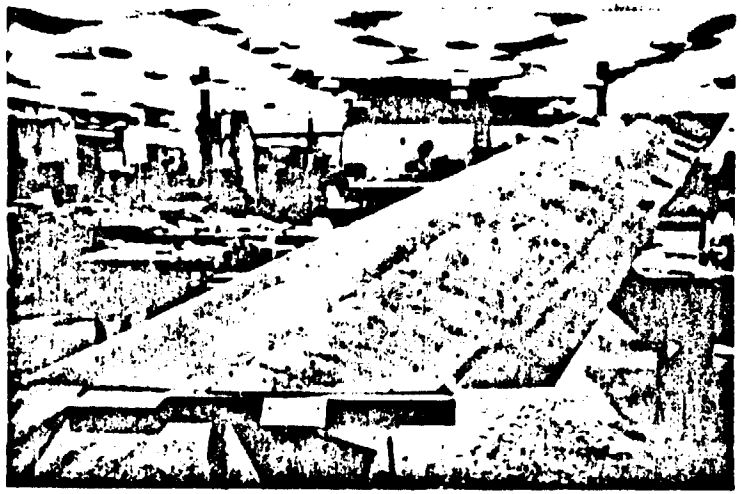
GP83-0667-00

GENERIC FIGHTER WING MODEL
ALTERNATE CONFIGURATIONS

$\Lambda_{LE} = 25°$ CONFIGURATION
WITH 10° LE, 10° TE FLAP DEFLECTIONS



$\Lambda_{LE} = 65°$ CONFIGURATION

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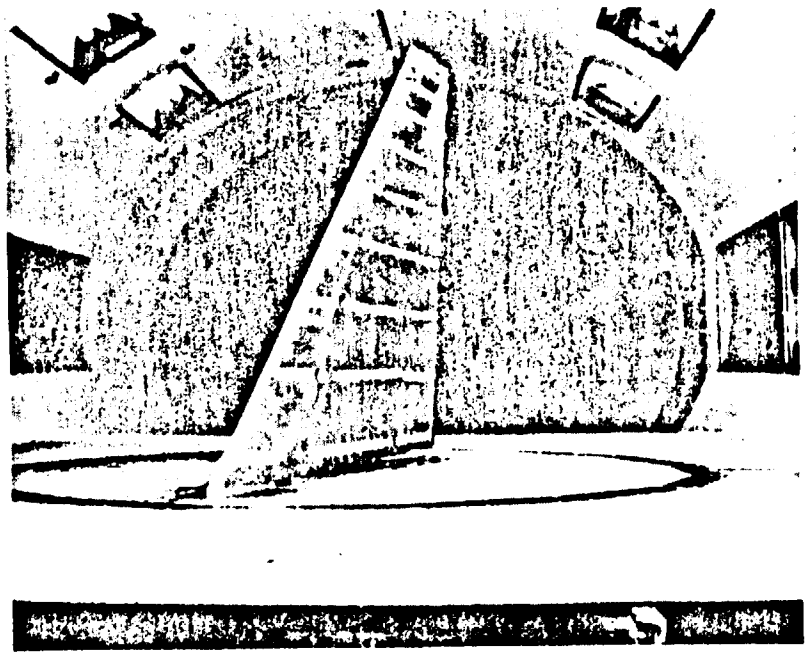
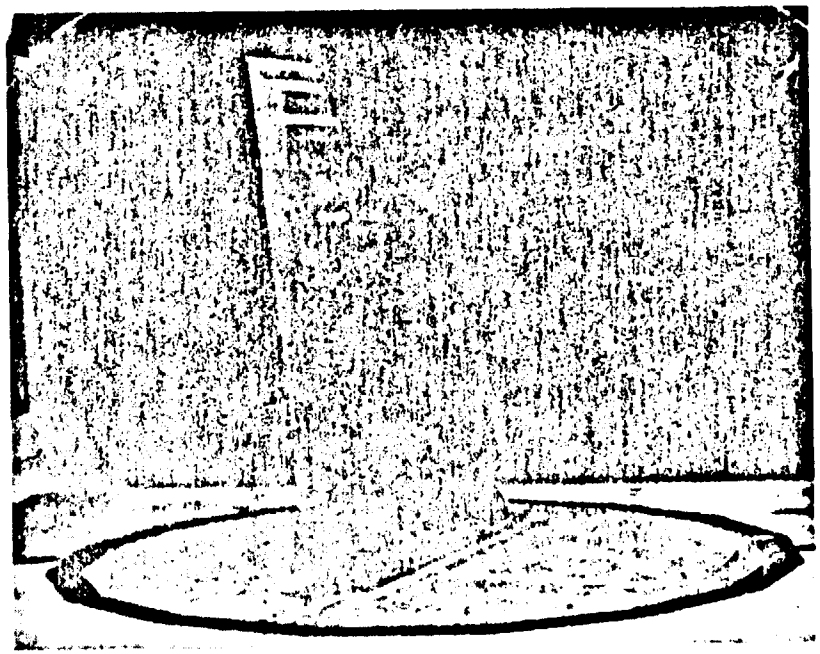
GP83-0007-70

Generic Fighter Wing Model in MIT Wright Brothers Wind Tunnel

Test Conducted May - June 1987
45° Wing Leading Edge Sweep



View Looking Downstream



View Looking Upstream

GP73-0280-201
MM-706

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C-7

CFD Validation Experiments at McDonnell Douglas Research Laboratories

FWS
86-222-293
McDonnell Douglas Research Laboratories

554

Cooperative Experimental Program with Ames Research Center

Low-Aspect-Ratio Wing/Body Experiment

- Experiments in Ames HRC-II facility
- Boundary-layer and wake multiple-orifice probe surveys in transonic flow about a low-aspect-ratio wing model

FWS
86-222-294
McDonnell Douglas Research Laboratories

555

Cooperative Experimental Program with Ames Research Center

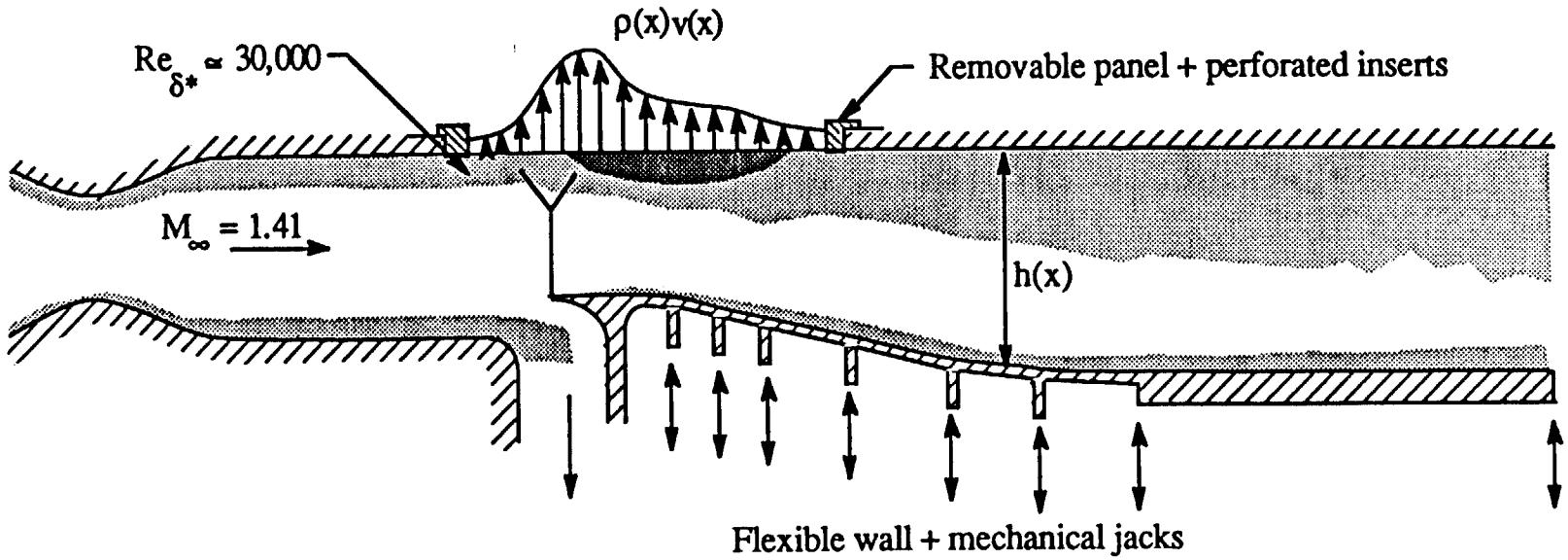
Hypersonic Nozzle-Plume Interaction Experiment

- Interaction of single-expansion-ramp (SERN) flowfields with hypersonic external flows
- Experiments in Ames Three-and One/Half-Foot Hypersonic Wind Tunnel
- Mach numbers 5, 7, 10, possibly 14
- Variations in nozzle configuration, jet gas temperature, gas composition
- Data to include nozzle static pressure distributions, flow visualization, and flowfield measurements

FWS
86-222-295
McDonnell Douglas Research Laboratories

Normal-Shock/Turbulent-Boundary-Layer Interactions, Modified by:

- Distributed mass removal
- Adverse pressure gradient in subsonic region



Nearly two-dimensional

$\rho(x)v(x)$, $h(x)$ both controlled and measured

Data: $p(x)$ top and bottom walls

$\overline{u}, \overline{v}, \overline{u'^2}, \overline{v'^2}, \overline{u'v'}$ vs x, y, z (LDV)

Aquisition in progress

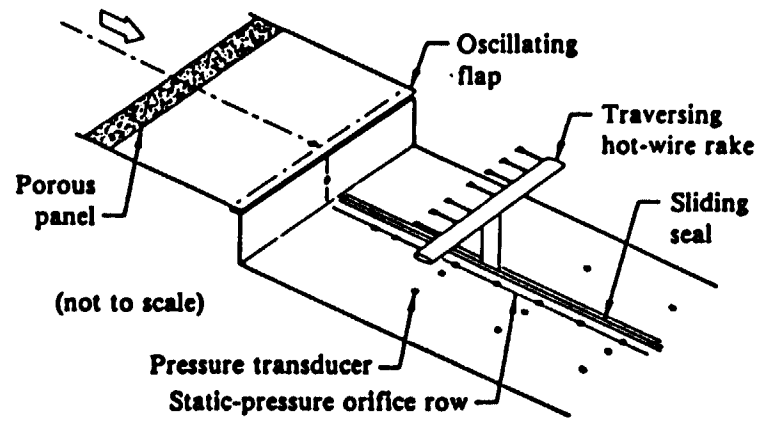
"Two-dimensionality" quantized

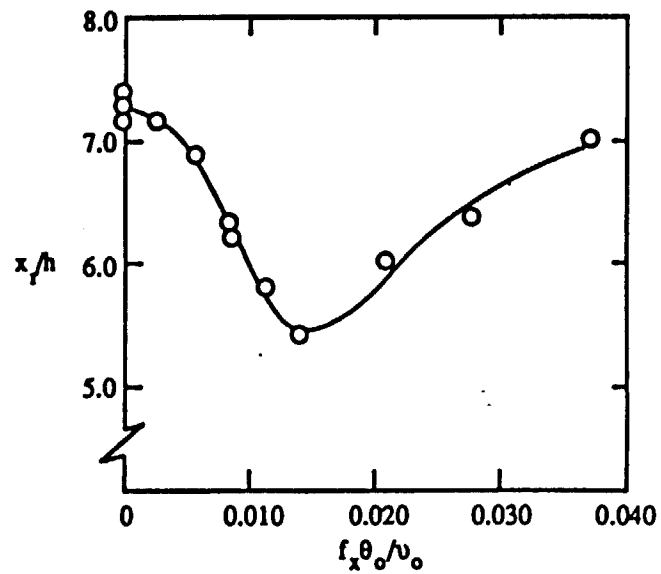
FWS
86-222-292
McDonnell Douglas Research Laboratories

Structure and Control of Flow Over a Backward-Facing Step

Features of experiment:

- Low-amplitude excitation with oscillating flap
- Mean and fluctuating wall-pressure measurements
- Hot-wire and LDV surveys
- Scanning laser light sheet flow visualization
- Image processing
- Emphasis on shear-layer vertical-structure dynamics





FWS
87-222-291
McDonnell Douglas Research Laboratories

GENERAL DYNAMICS' PERSPECTIVE ON CFD CODE CALIBRATION/VALIDATION

PRESENTED AT

FIRST NASA CFD VALIDATION WORKSHOP
AMES RESEARCH CENTER
14-16 JULY 1987

BY

I. C. BHATELEY
G. H. HULL

N92-70945

OUTLINE

DEFINITIONS

CODE CALIBRATION CASES

CODE VALIDATION CASES

VALIDATION EXPERIMENTS

NEEDS FOR EXPERIMENTAL DATA

ADVANCED EXPERIMENTAL TECHNIQUES

GOVERNMENT/INDUSTRY COOPERATION

SUMMARY

DEFINITIONS

CALIBRATION:

- o COMPARISON OF COMPUTATIONAL DATA WITH EXPERIMENTAL DATA

  REALISTIC GEOMETRIES
  SPECIFIC PARAMETERS
  LIMITED RANGE

- o PROVIDES A MEASURE OF CODE'S CAPABILITY FOR USE ON A SPECIFIC APPLICATION.

VALIDATION:

- o COMPARISON OF COMPUTATIONAL DATA WITH EXPERIMENTAL DATA

  ACCURACY AND LIMITATIONS OF EXPERIMENTAL DATA MUST BE KNOWN
  CODE'S NUMERICAL ALGORITHMS AND GRID EFFECTS MUST BE KNOWN
  DETAILED SURFACE AND FLOWFIELD COMPARISONS

- o PROVIDES A MEASURE OF CODES CAPABILITY TO ACCURATELY MODEL THE CRITICAL PHYSICS OF THE FLOW.

CATEGORIES OF EXPERIMENTATION

FOUR CATEGORIES OF EXPERIMENTS ARE IMPORTANT AND NECESSARY TO BUILD A MATURE CFD CAPABILITY. EXPERIMENTS ARE DESIGNED TO:

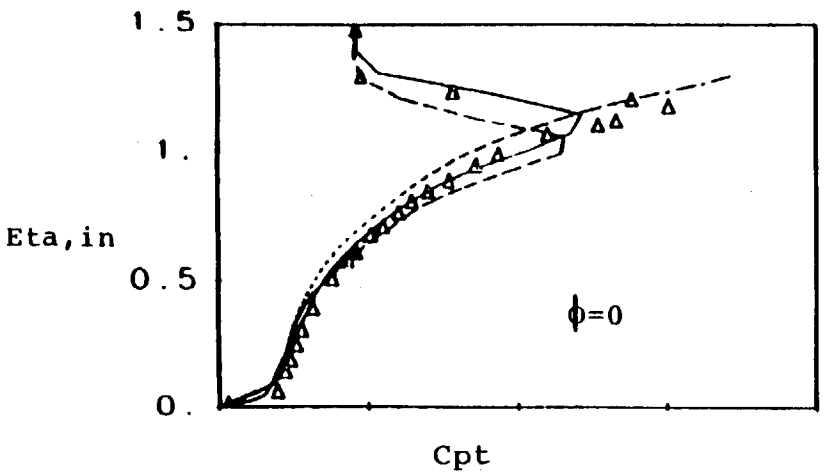
1. UNDERSTAND FLOW PHYSICS
2. DEVELOP PHYSICAL MODELS FOR CFD CODES
3. CALIBRATE CFD CODES
4. VALIDATE CFD CODES

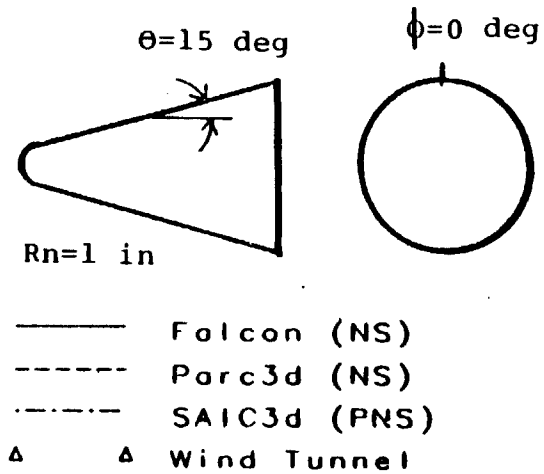
CODE CALIBRATION CASES

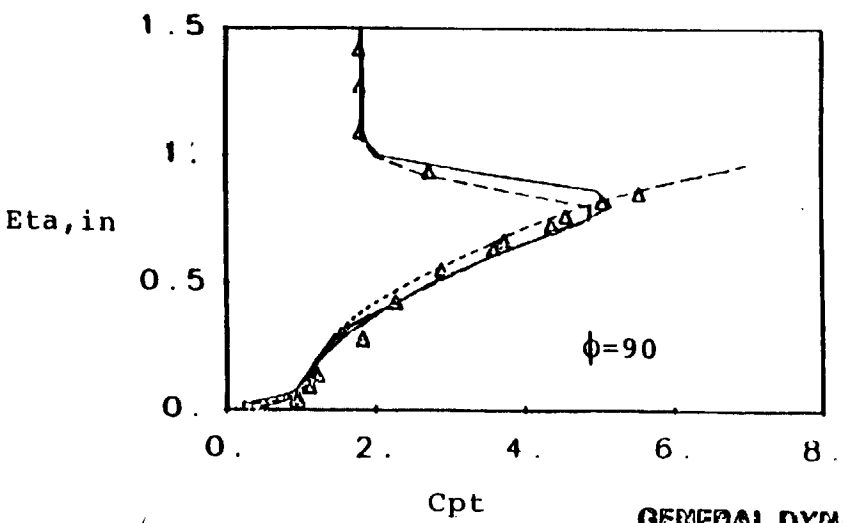
HYPERSONIC BLUNTED CONE

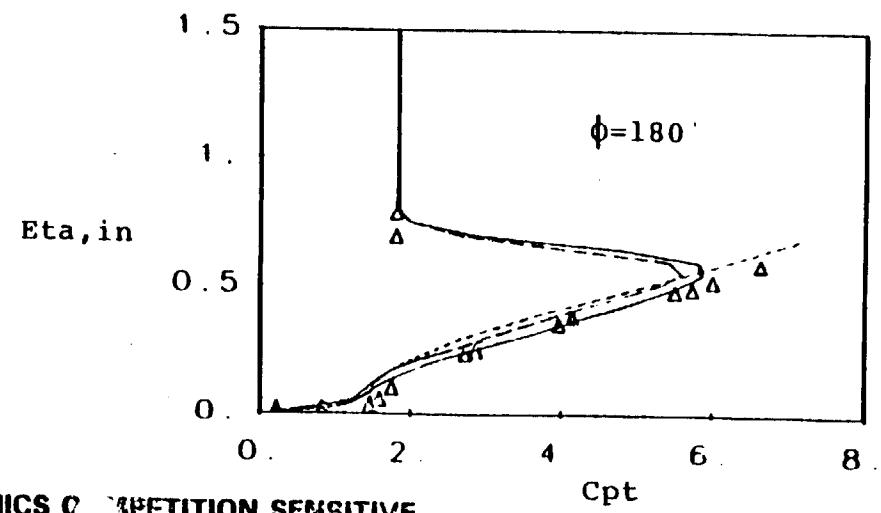
NASA TN D-2969

PITOT PRESSURE RAKE @ x = 3.59 IN
MACH = 10.6 ALPHA = 5 DEG.







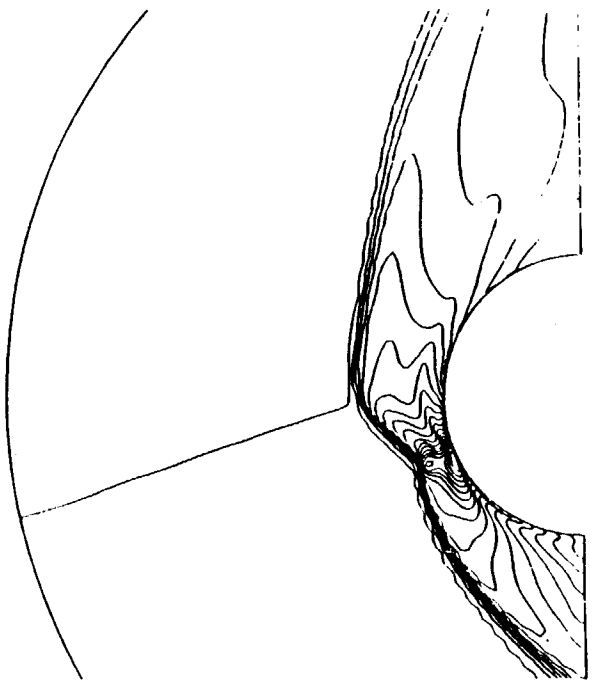


HYPERSONIC WEDGE/CYLINDER

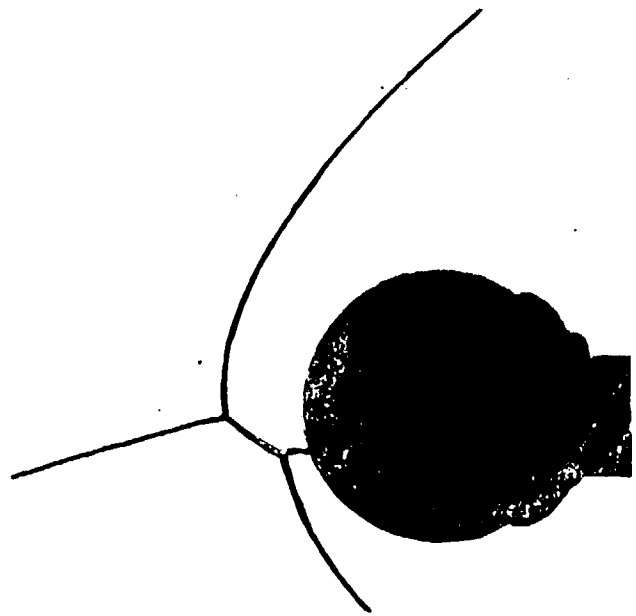
ALLAN R. WIETING -- PHD DISSERTATION

SHOCK STRUCTURE COMPARISON

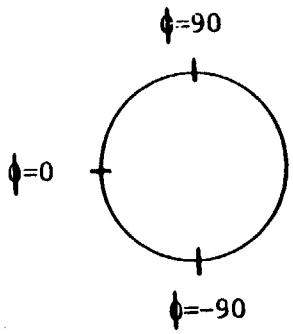
MACH = 6.46 RE = 4.0×10^5 / FT



FALCON DENSITY CONTOUR



WIND TUNNEL SCHLIEREN

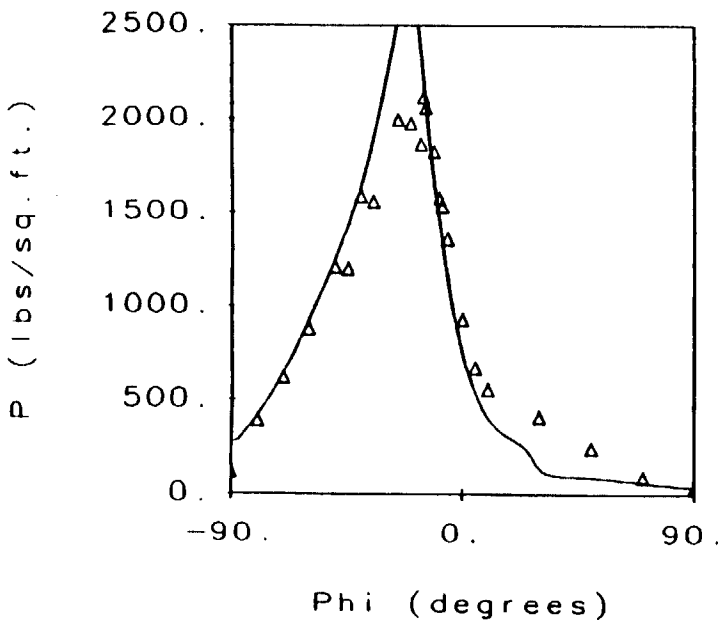


HYPERSONIC WEDGE/CYLINDER

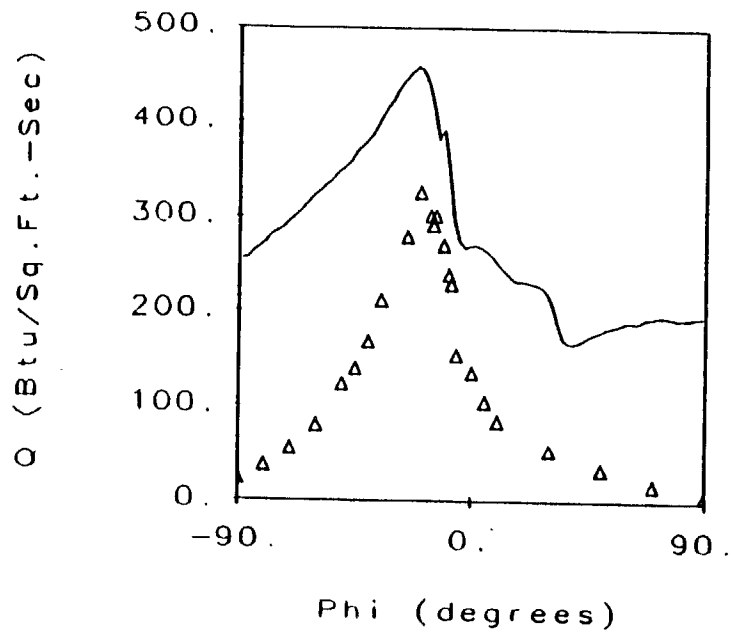
WALL MEASUREABLE QUANTITIES

MACH = 6.46 RE = 4.0×10^5 / FT

FALCON
Wieting Data

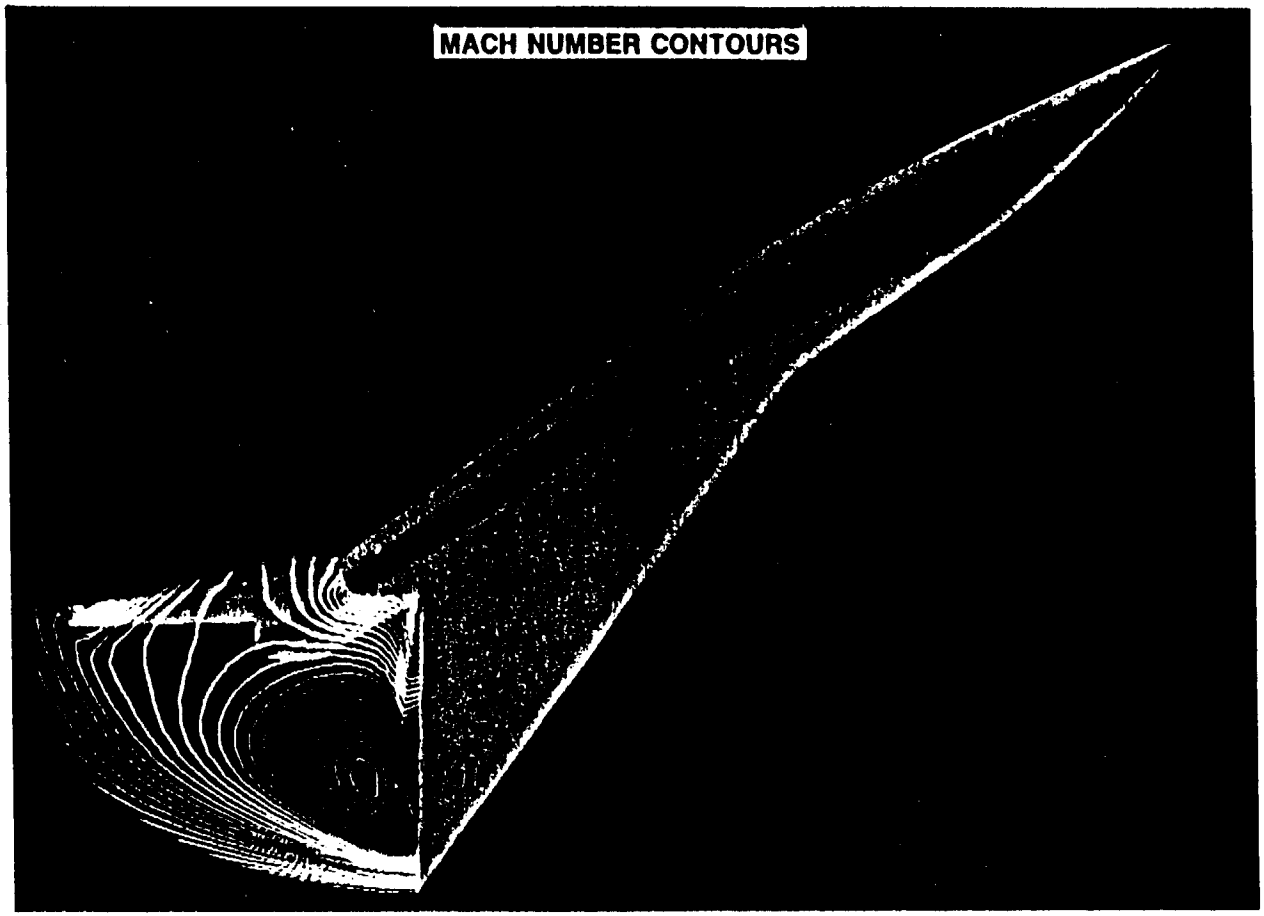


CYLINDER PRESSURE DISTRIBUTION



CYLINDER HEAT TRANSFER DISTRIBUTION

WING VORTEX DEFINED BY MACH CONTOURS



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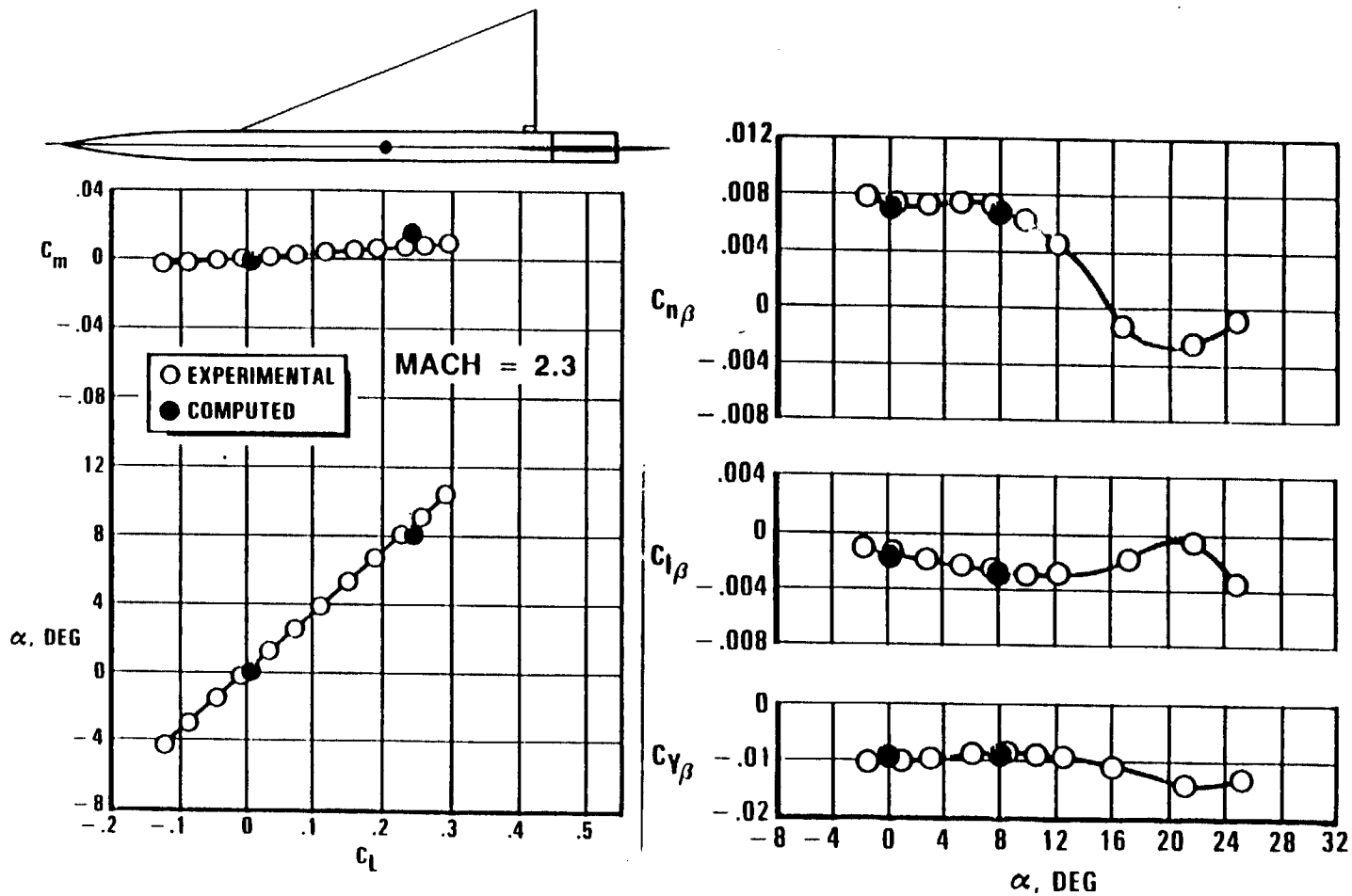
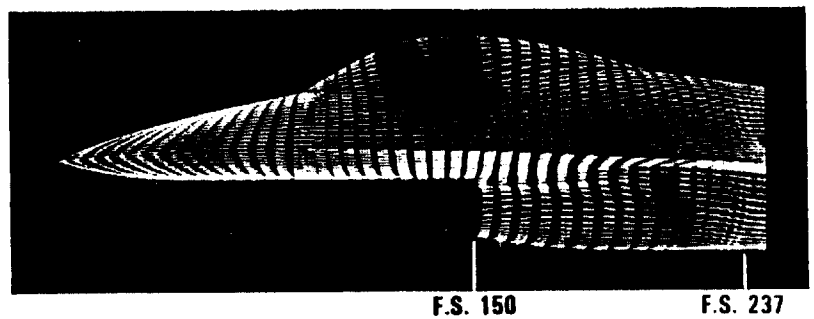
CLASSIFICATION
PAGE NUMBER

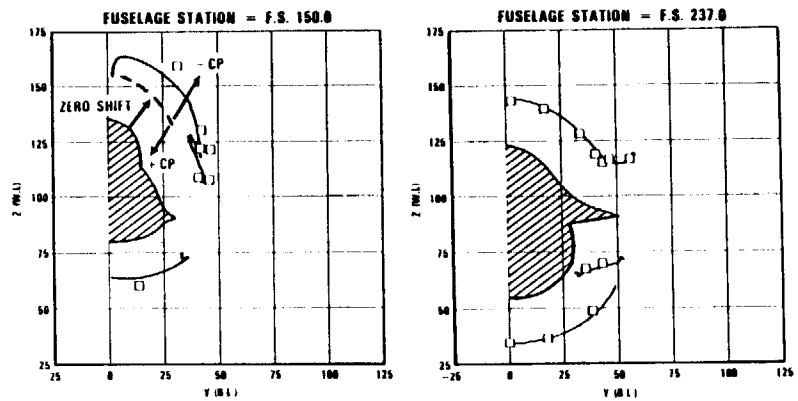

O EXPERIMENTAL
● COMPUTED
MACH = 2.3
C_m
.04
0
-.04
-.08
α, DEG
12
8
4
0
-4
-8
-.2
-.1
0
.1
.2
.3
.4
.5
C_L
C_{n_β}
.012
.008
.004
0
-.004
-.008
C_{l_β}
.004
0
-.004
-.008
C_{Y_β}
0
-.01
-.02
-8
-4
0
4
8
12
16
20
24
28
32
α, DEG

M = .9 $\alpha = 4^\circ$

VELOCITY VECTORS

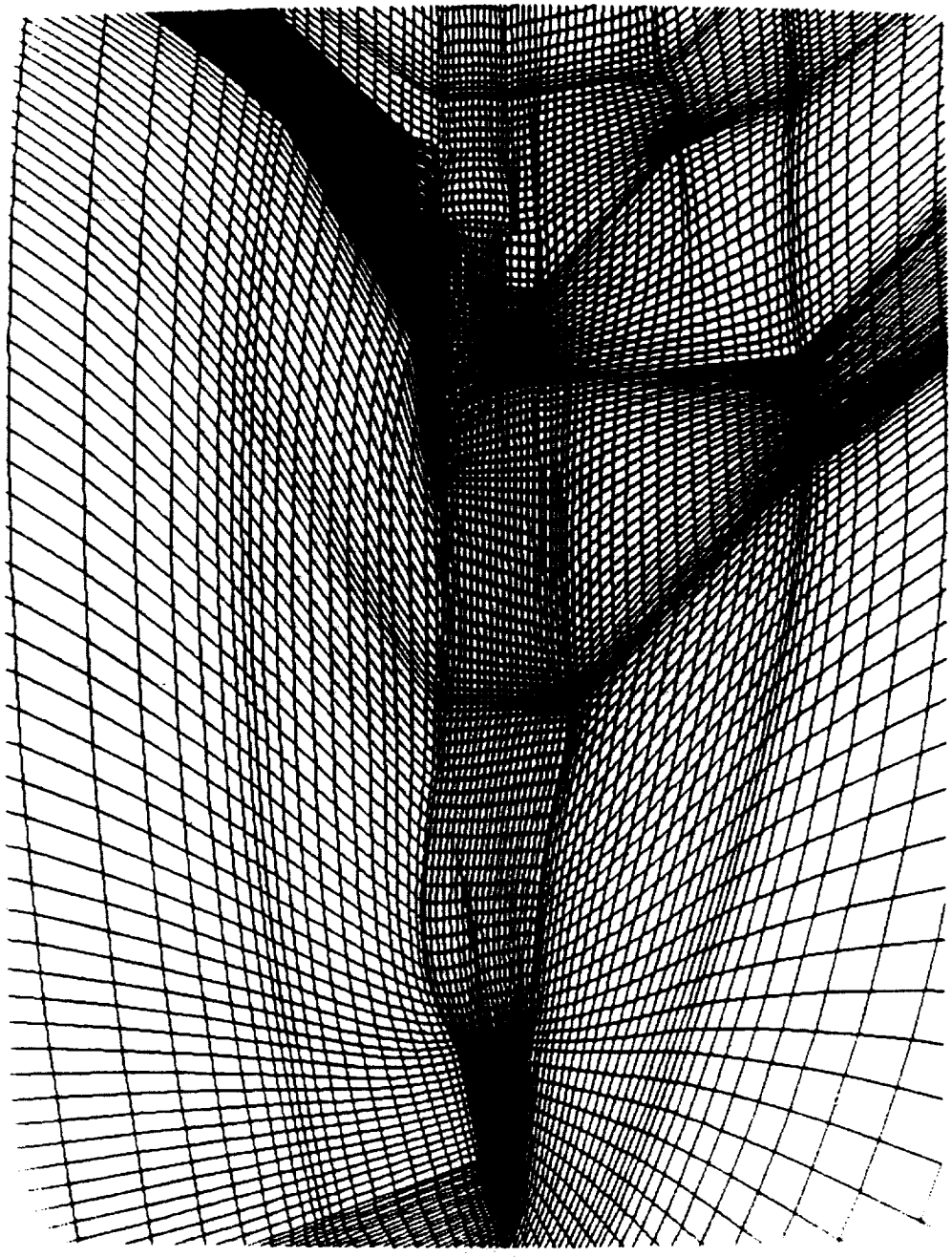


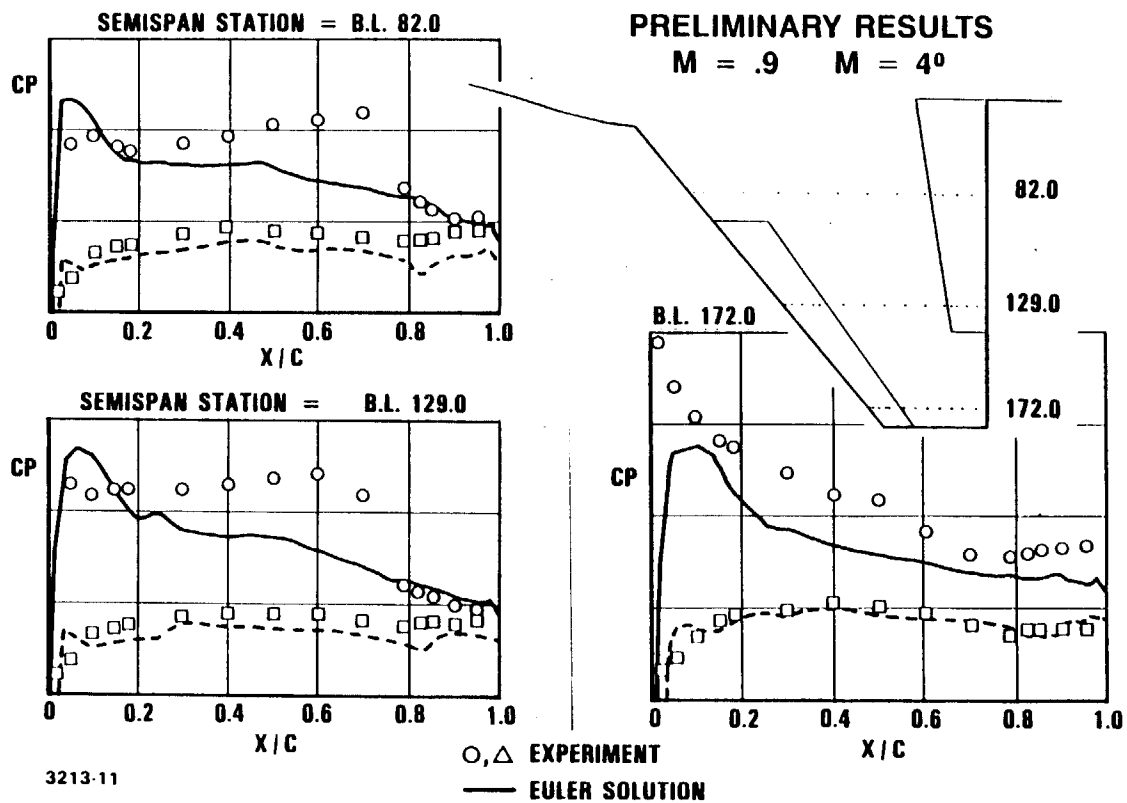
PRESSURE DISTRIBUTIONS



□ *EXPERIMENT*
— *EULER SOLUTION*

3213-10

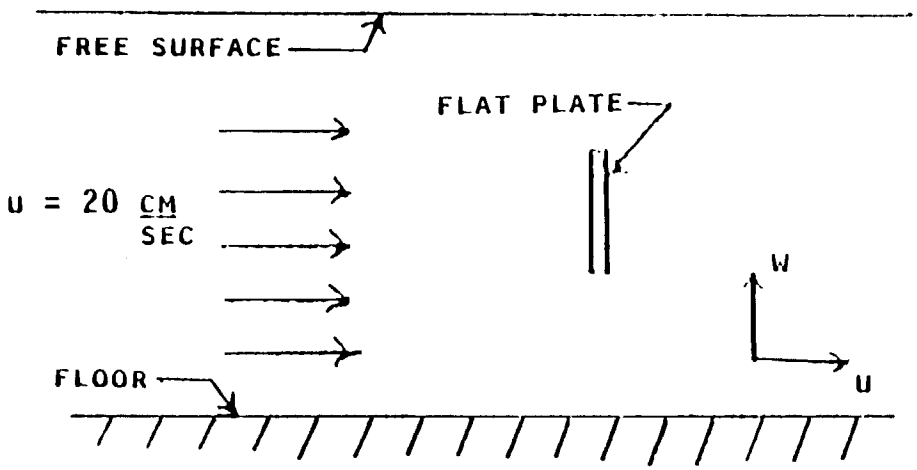



PRELIMINARY RESULTS
M = .9 M = 4°
SEMISPAN STATION = B.L. 82.0
CP
0 0.2 0.4 0.6 0.8 1.0
X / C
SEMISPAN STATION = B.L. 129.0
CP
0 0.2 0.4 0.6 0.8 1.0
X / C
B.L. 172.0
82.0
129.0
172.0
CP
0 0.2 0.4 0.6 0.8 1.0
X / C
○,△ EXPERIMENT
EULER SOLUTION
3213-11

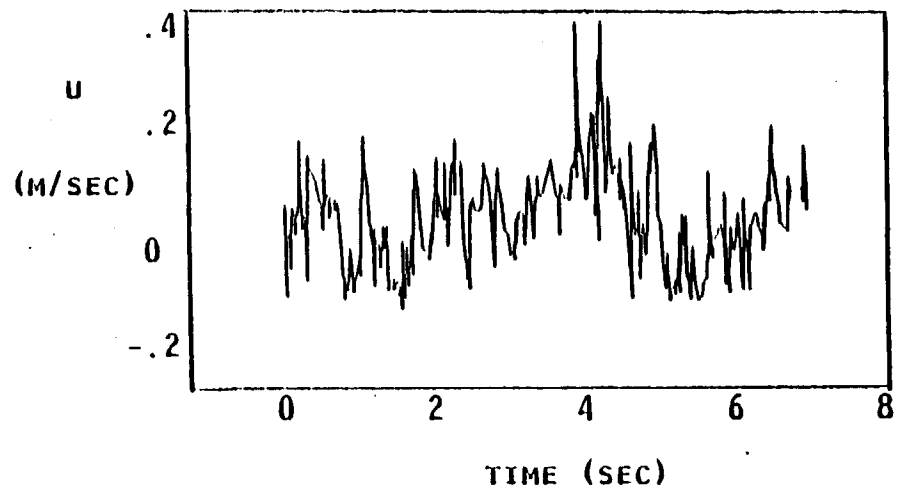
GENERAL DYNAMICS' EXPERIMENTAL PROJECTS FOR CODE VALIDATION

3-D TURBULENT FLOW BEHIND A 2-D FLAT PLATE
WATER TUNNEL LDV MEASUREMENTS

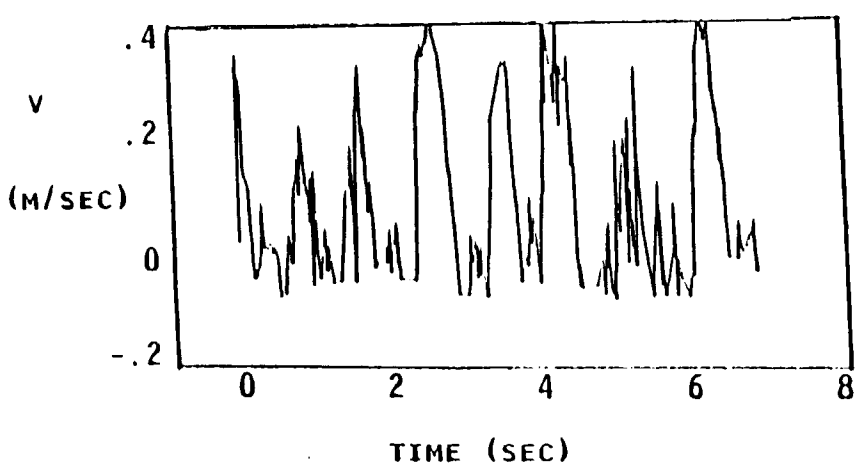
SIDE VIEW OF 2-D CHANNEL



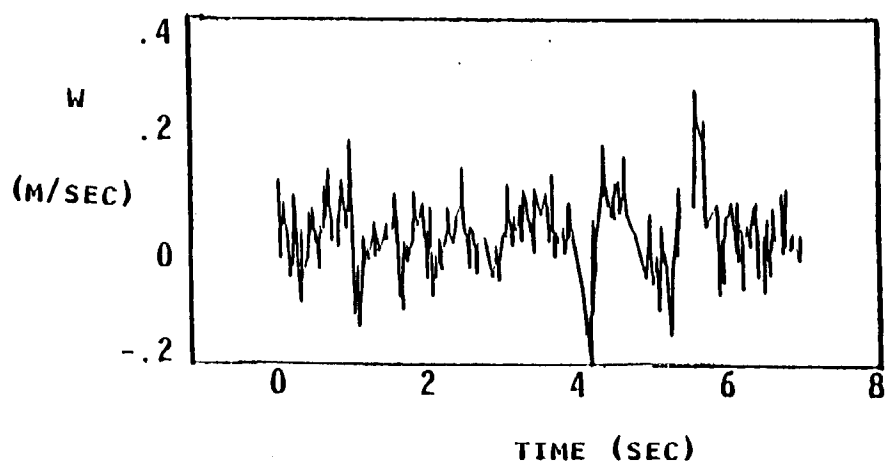
AXIAL VELOCITY



LATERAL VELOCITY



VERTICAL VELOCITY



NEEDS FOR ADVANCED EXPERIMENTAL DATA FOR CFD CODE MATURATION

- o BOUNDARY-LAYER FLOWS

  TRANSITION
  TURBULENCE

- o SHOCK-SHOCK AND SHOCK-WAVE BOUNDARY LAYER INTERACTIONS
- o HEAT TRANSFER/SKIN FRICTION
- o UNSTEADY, SEPARATED FLOW
- o NON-EQUILIBRIUM REACTING GAS FLOWS
- o DUCTED FLOW OF NON-AIR GASEOUS MIXTURES

ADVANCED EXPERIMENTAL TECHNIQUES

NASA SHOULD AGGRESSIVELY PURSUE THE CAPABILITY TO RAPIDLY MEASURE FLOWFIELD PARAMETERS.

- LASER DOPPLER VELOCIMETRY
- LASER HOLOGRAPHIC INTERFEROMETRY
- LASER INDUCED LUMINESCENCE
- FLOW VISUALIZATION
- SKIN FRICTION/HEAT TRANSFER
- DEVELOP METHODS FOR ESTABLISHING ACCURACY OF MEASUREMENTS

GOVERNMENT/INDUSTRY COOPERATION

- NASA SHOULD TAKE LEAD

  CONTINUE VALIDATION WORKSHOPS
  DEVELOP FACILITIES, EQUIPMENT, AND TEST TECHNIQUES
  DEVELOP COMPUTERIZED DATABASE OF EXPERIMENTAL DATA

    EXISTING AND NEW
    COMMON FORMAT

  DEVELOP VALIDATION CRITERIA

- INDUSTRY SHOULD SUPPORT NASA BY

  COORDINATING PROJECTS WITH NASA
  SUBMITTING INHOUSE CFD COMPUTATIONS TO NASA
  MONITORING AND SUPPORTING NASA TEST PROGRAMS
  SUPPLYING EXISTING WIND TUNNEL MODELS WHEN NEEDED

SUMMARY

- Code Calibration/Validation is essential for the maturation of CFD technology.
- General Dynamics is committed to CFD development.

  Code development
  Calibration/Validation
  Advanced experimental techniques
  Validation experiments

- General Dynamics is committed to work with NASA to maturate CFD methods.

NB 87-109
JULY 1987

CFD Validation Workshop

14-16 July 1987

Mike George

NORTHROP

N92-70946

578

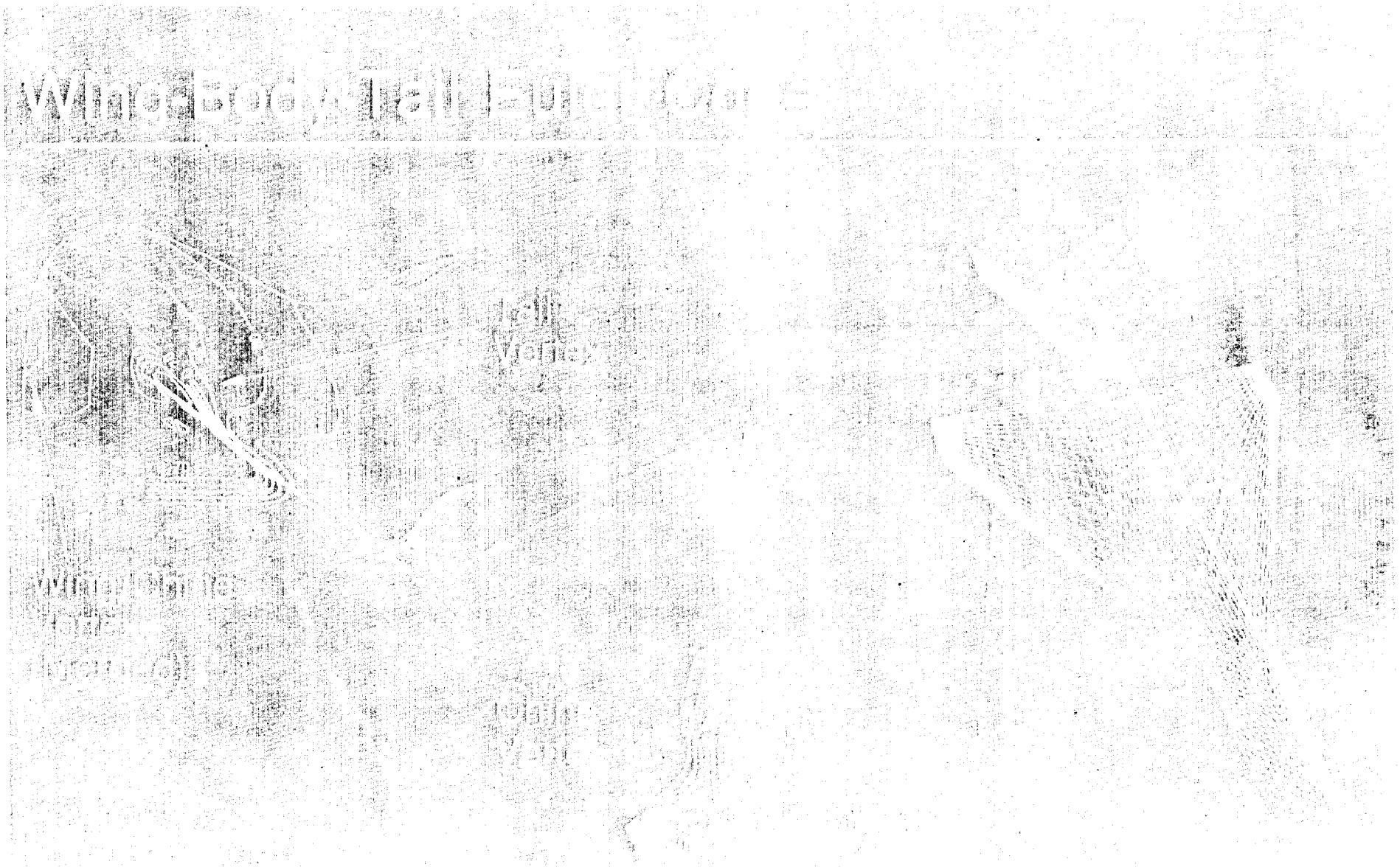
Approach/Philosophy for CFD Validation

- Emphasis on Validation of Boundary Conditions, Grid Structure, and Turbulence Modeling, Not on Validation of Navier-Stokes, Euler, etc, Algorithms in General
  - Tests Should Consist of a Range of Configurations, Specifically Designed To Validate Grid Structure and Boundary Conditions
  - Emphasis on the Determination of What Physics Is Needed for Different Problems
  - Experiments Should Provide the Same Information Capability as Provided by CFD Methods

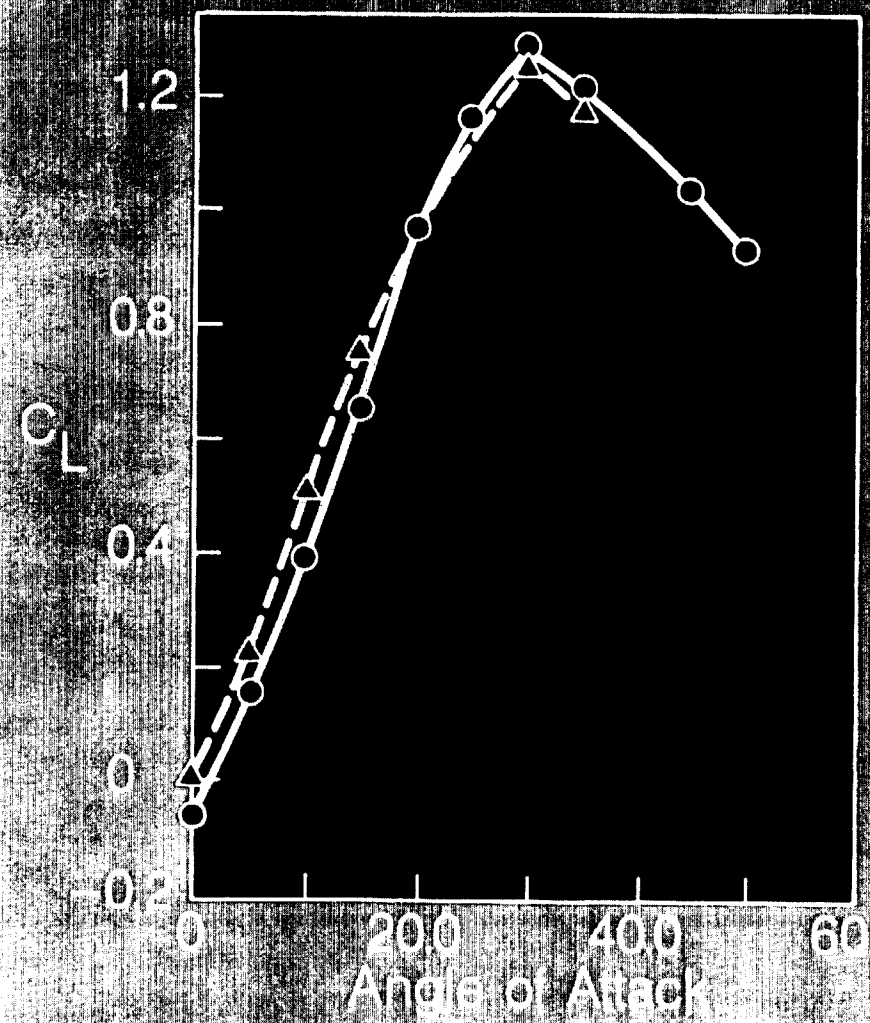
Current CFD Validation Efforts

- Ability of Navier-Stokes Codes To Model Structured Vortex Phenomena, e.g., High Angle-of-Attack Fighter Flowfields

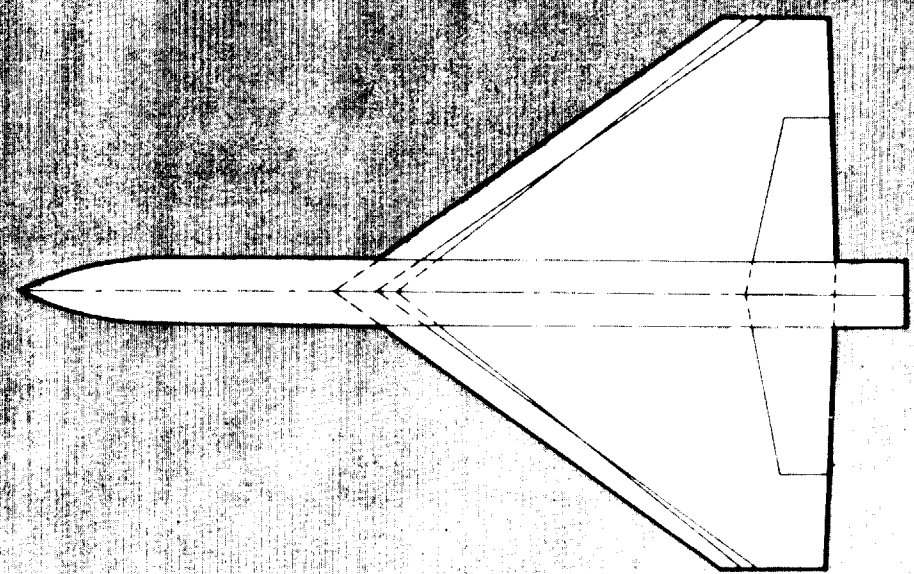
- Ability of Navier-Stokes Codes To Model Nozzle/Exhaust Flowfields



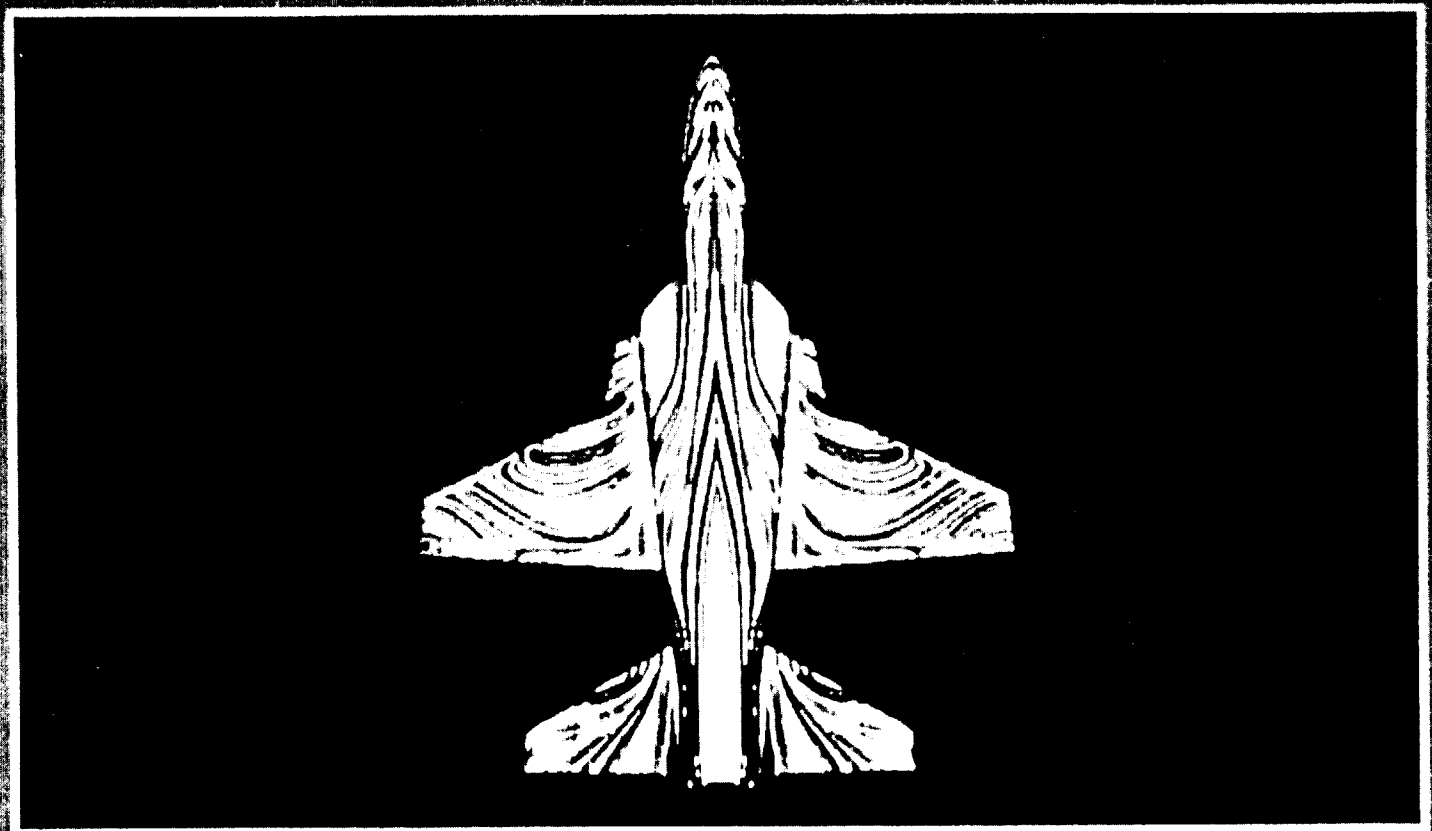
Experimental Verification



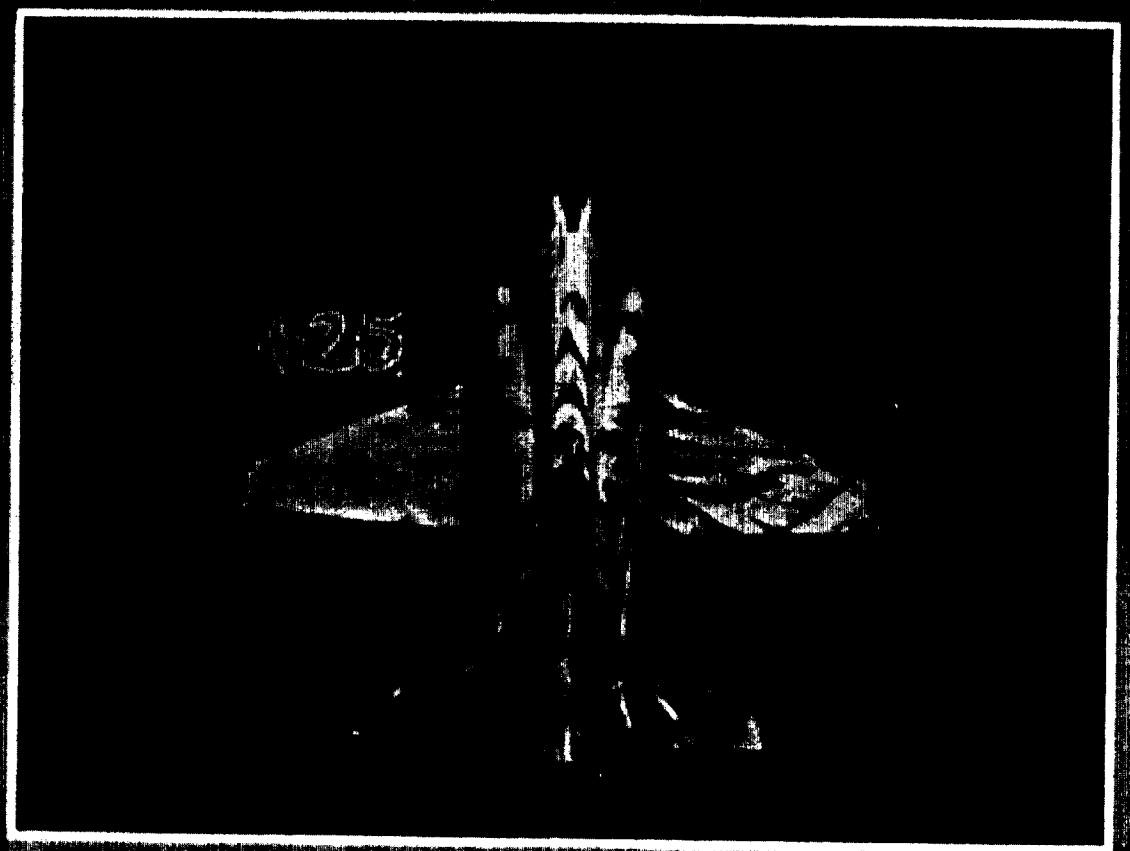
Legend:
△ Experiment
○ Computation

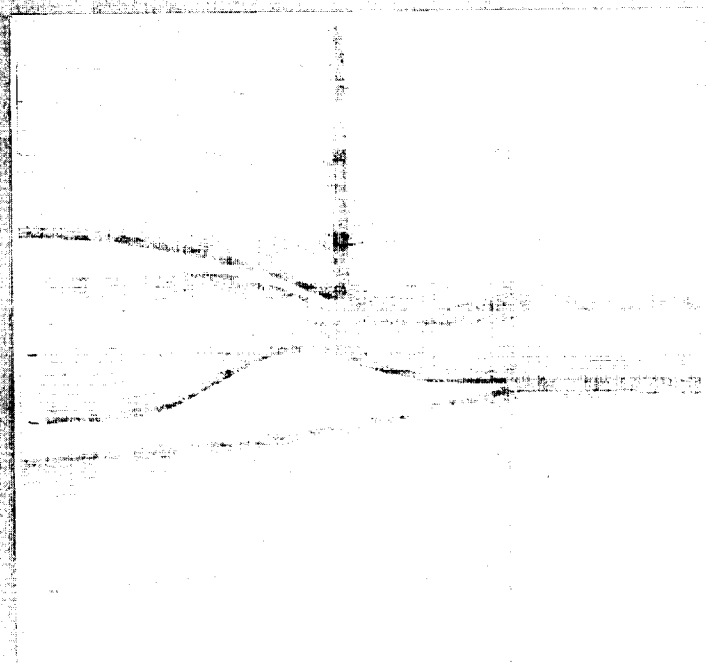


F-20 Euler Simulated Oil Flow
(M = 0.26, α = 25°)

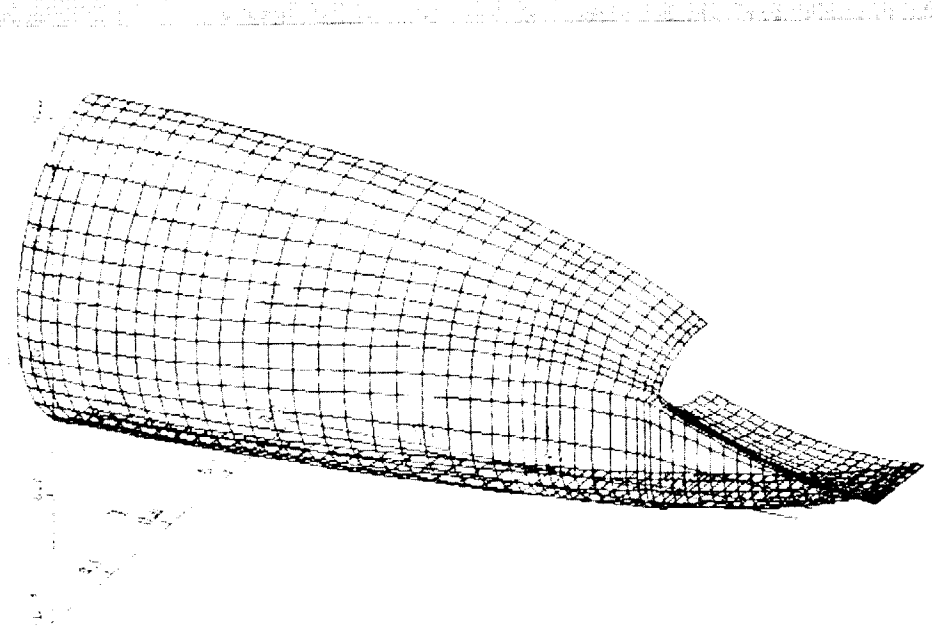


F-20 Wind Tunnel Test Oil Flow
(M = 0.26, α = 25°)

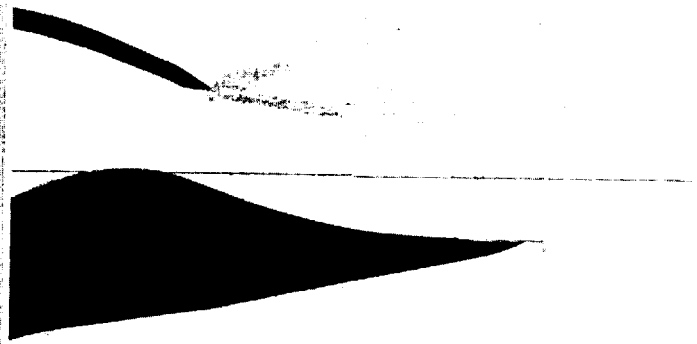




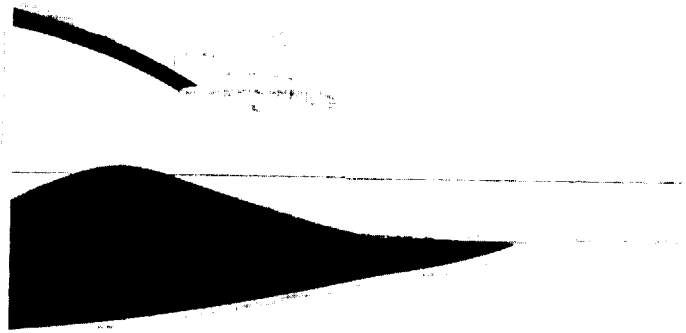
2-D Navier-Stokes — ARC2D
320 × 100 Grid



3-D Euler — FLO57
81 × 21 × 42 Grid



Euler — 200 × 50 Grid



Navier-Stokes — 320 × 100 Grid

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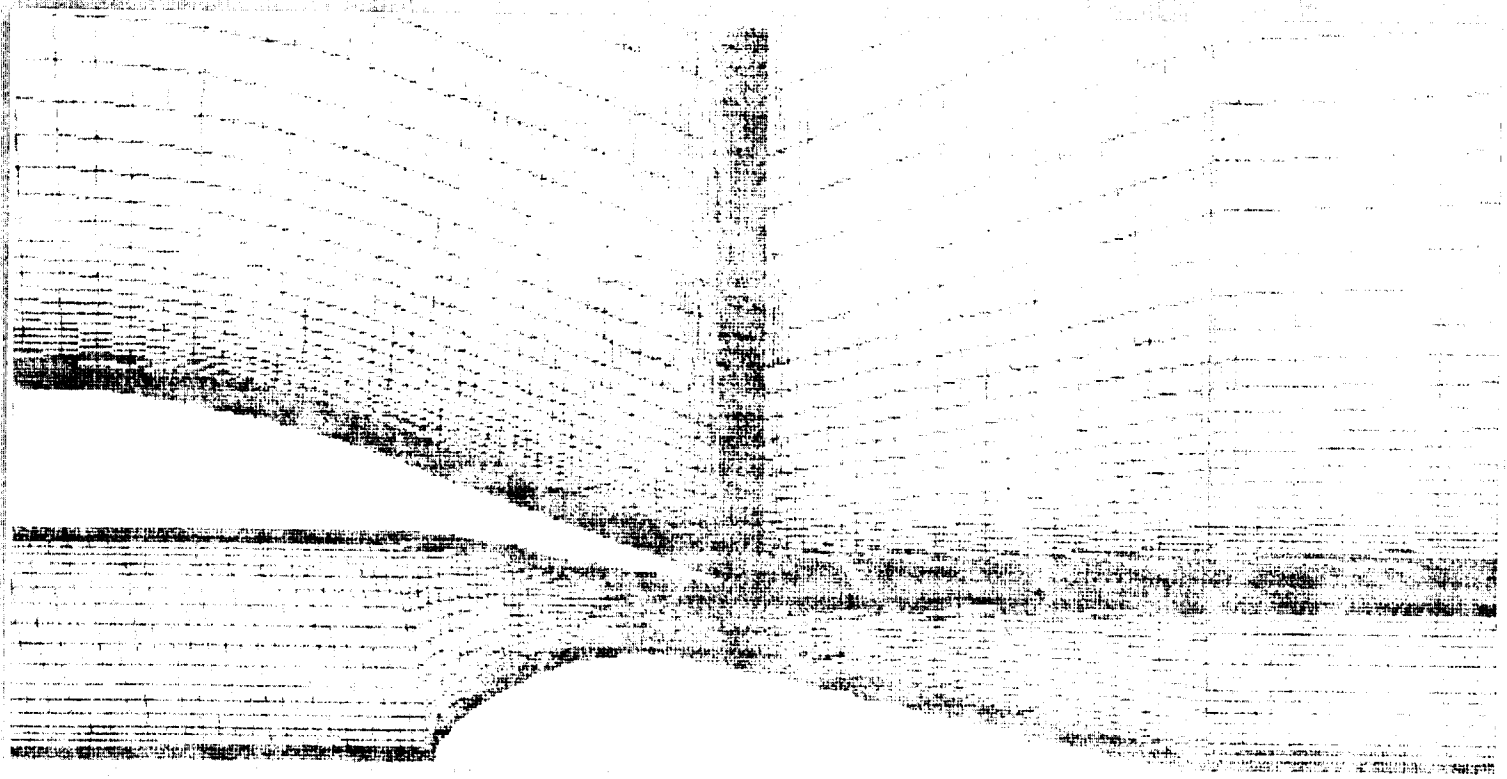
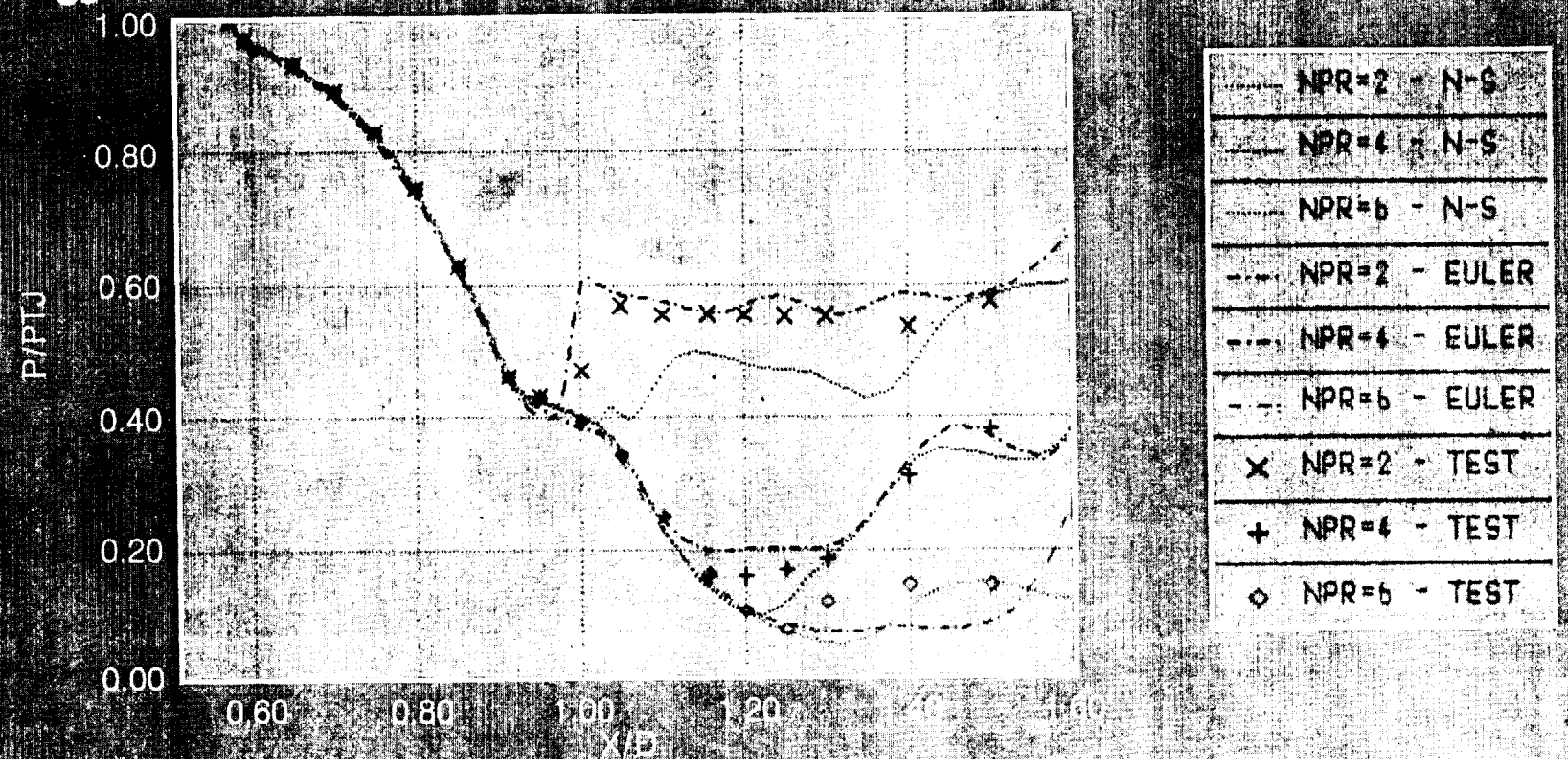


Comparison of Euler and Navier-Stokes Wedge Surface Pressures for 2-D Wedge Nozzle Using ARC2D

$M_\infty = 0.8$



87-51492
3Q NS II

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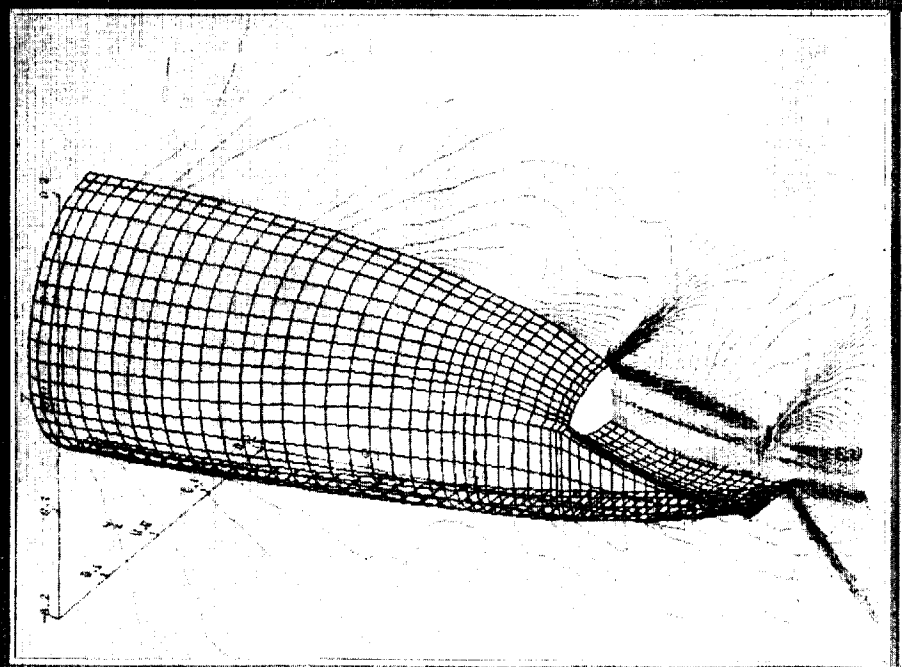
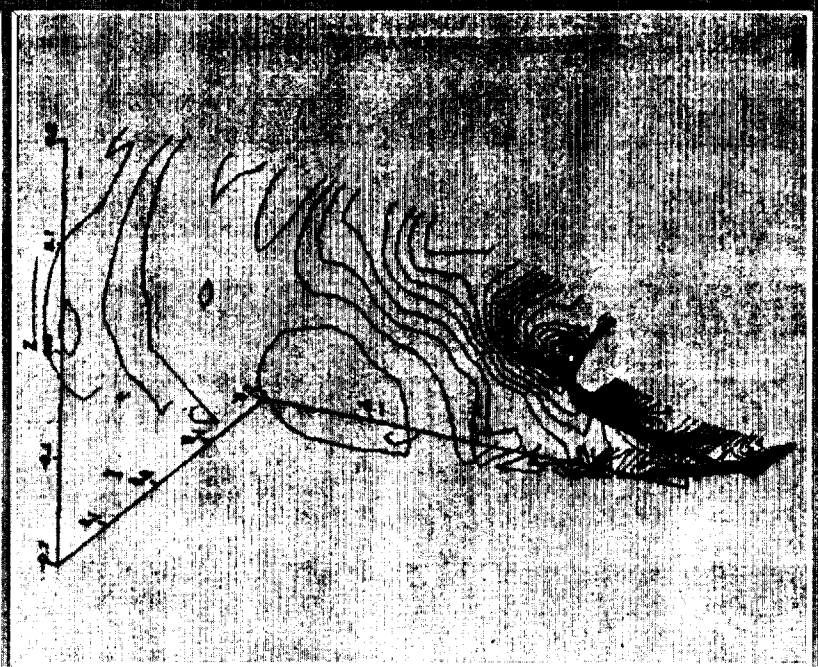
Euler Calculations for 3-D SERN Using FLO57

$M_\infty = 1.4$, NPR = 5.0, 81 × 21 × 42 Grid



Center Plane Mach Controls

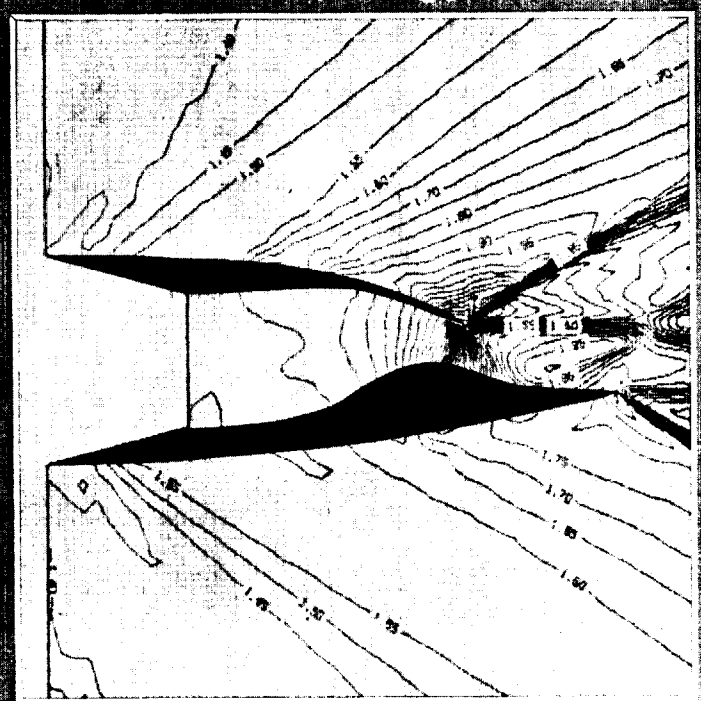


Surface Mach Contours

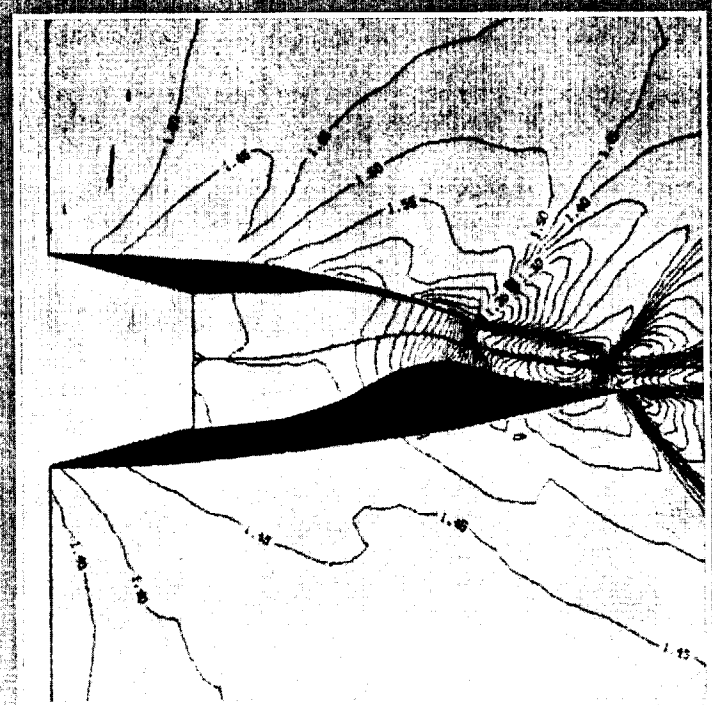
87-51489
3Q NS II

Euler Code Validation for 2-D and 3-D Nozzle Afterbody Applications

SERN-FLO57, $M_\infty = 1.4$, NPR = 5.0



2-D — 81 × 91 Grid



3-D — 81 × 21 × 42 Grid

Tests Northrop Would Like To See

Nozzle

- SERN-Type
- Ejectors
- Hot Gas

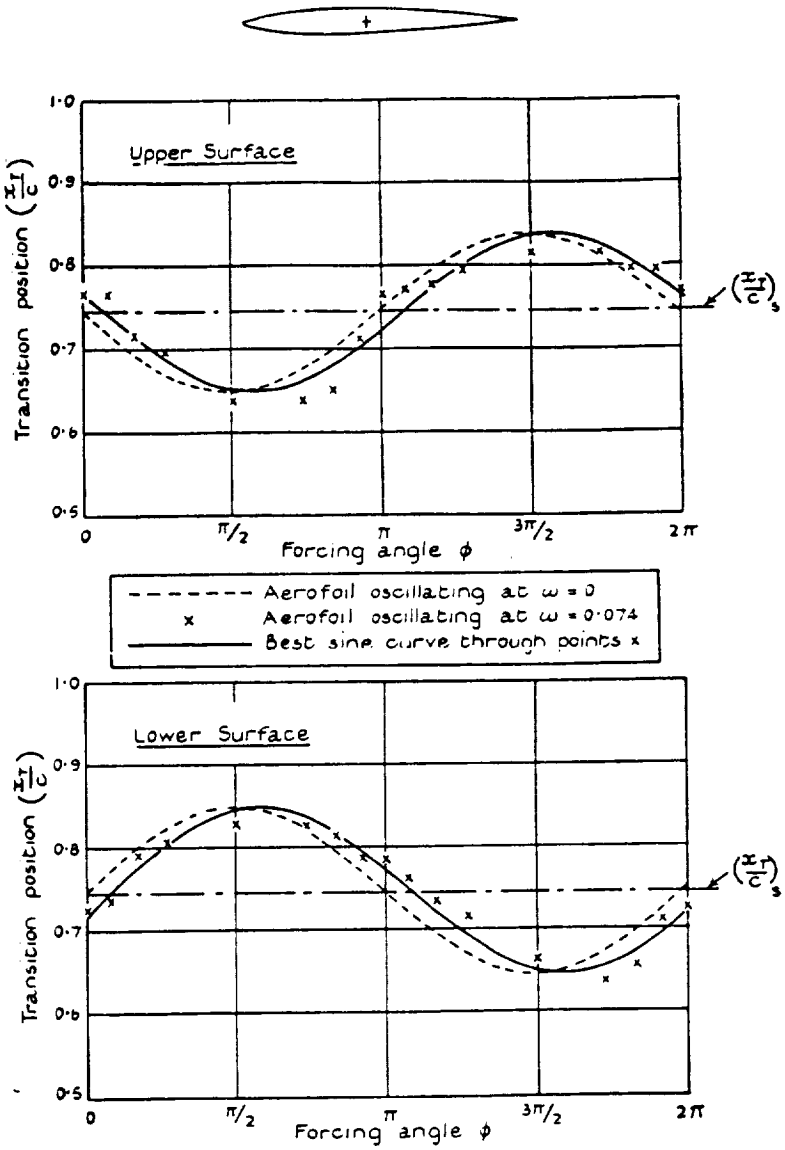
Fighter-Type Aircraft

- Complex Vortex Phenomena
  - Vortex-Tail Interaction at High Alpha
- Unsteady Characteristics
  - Rigid
  - Aeroelastic
- Incorporate Flowing Inlet and Nozzle

87-51499

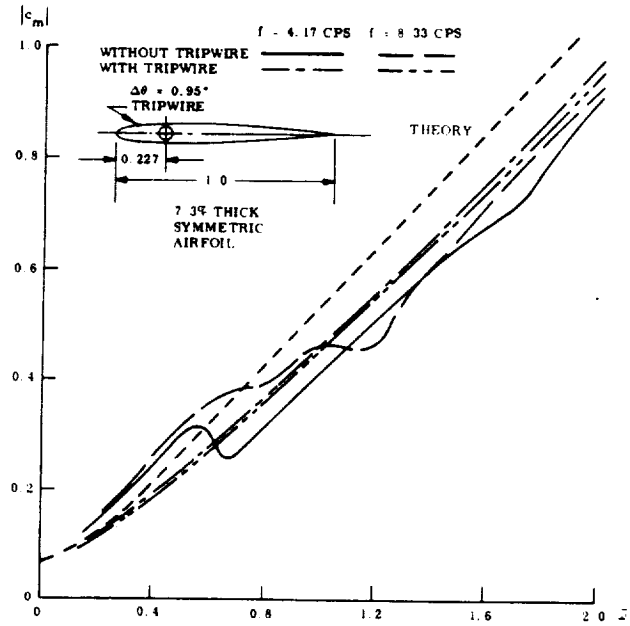
L. Ericsson

N92-70947

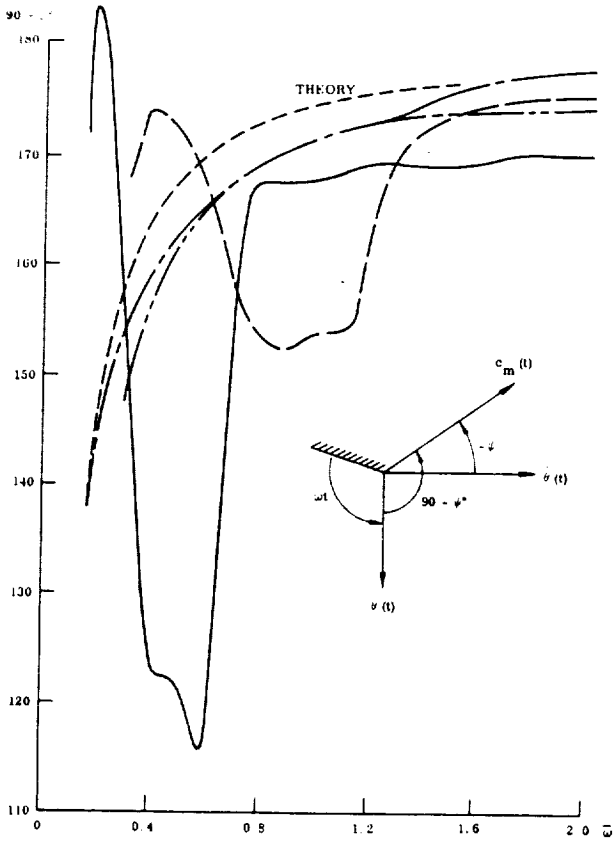


Typical measurements of the movement of the transition regions in a cycle. $\alpha_0 = 0$ deg. $\theta_0 = 2$ deg. Axis at 0·445c. $M = 0{\cdot}82$.

L. Ericsson

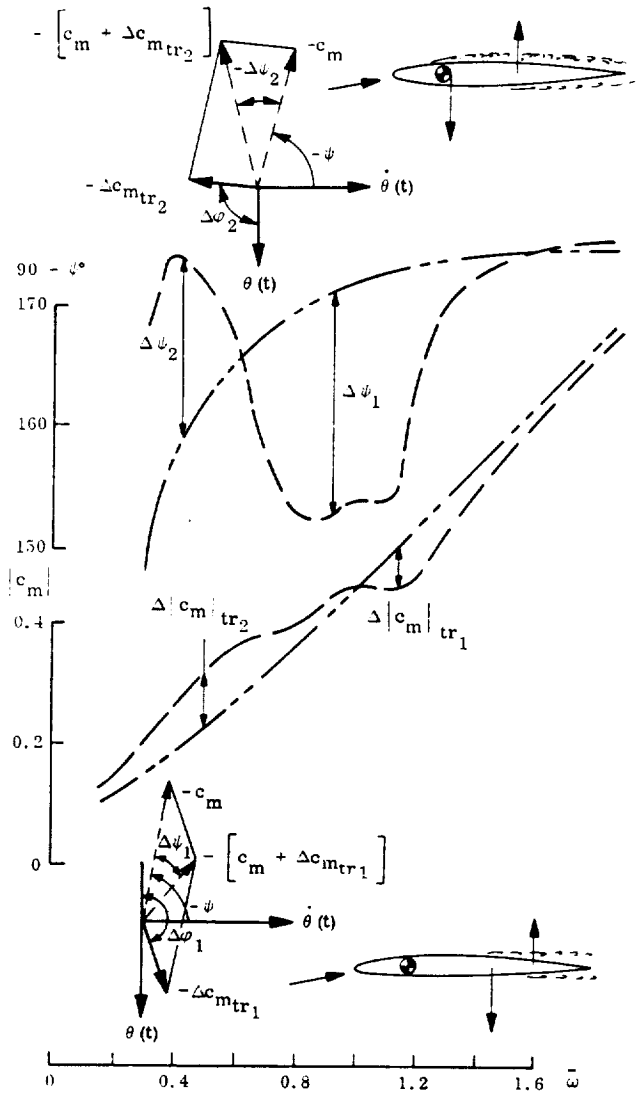


a. MOMENT AMPLITUDE VARIATION WITH FREQUENCY

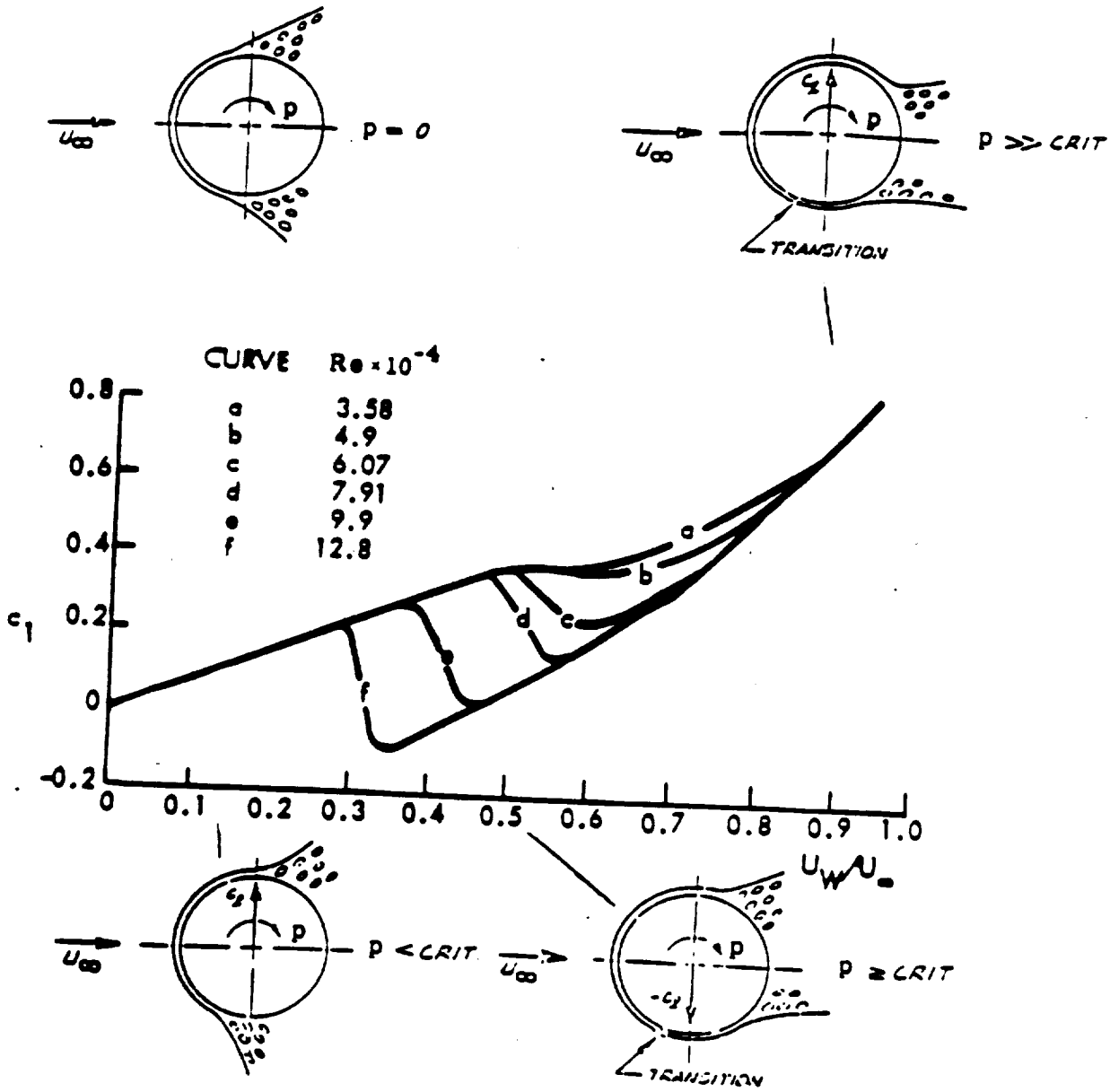


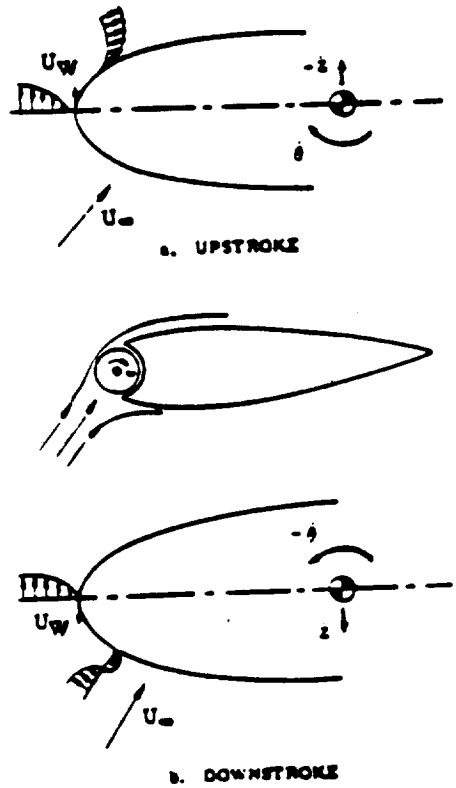
b. PHASE LEAD VARIATION WITH FREQUENCY

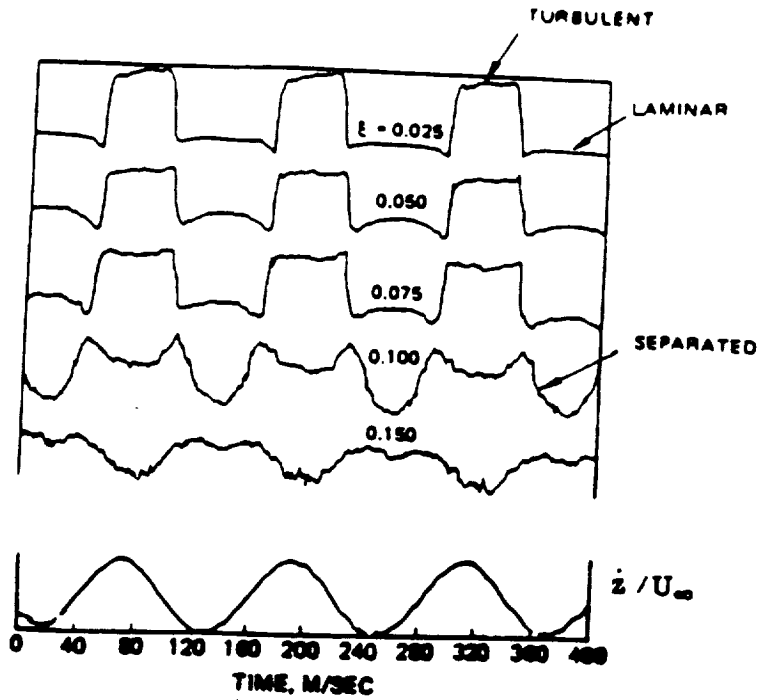
Effect of trip wire on the dynamic characteristics[8].



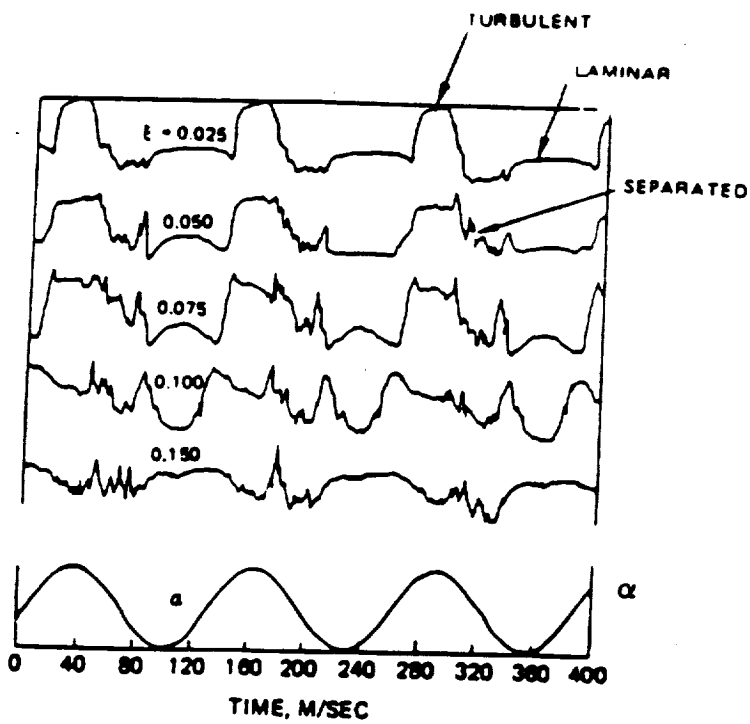
Effect of boundary-layer transition induced loads on dynamic characteristics.


p = 0
p >> CRIT
TRANSITION
CURVE Re × 10^-4
a 3.58
b 4.9
c 6.07
d 7.91
e 9.9
f 12.8
c_l
0.8
0.6
0.4
0.2
0
-0.2
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
U_W/U_∞
p < CRIT
p ≥ CRIT
TRANSITION

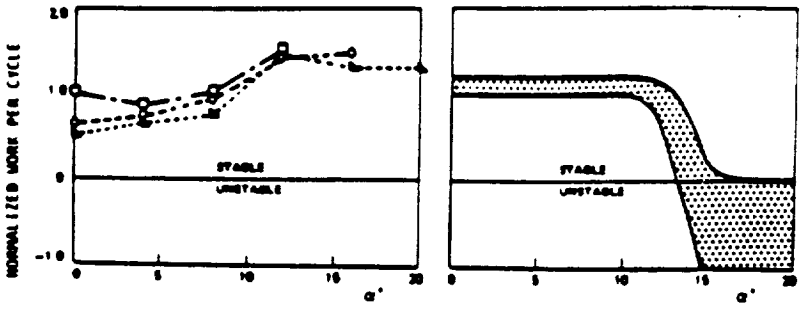

U_W
$-\dot{z}$
$\dot{\theta}$
U_∞
a. UPSTROKE
$-\dot{\theta}$
U_W
$\dot{z}$
U_∞
b. DOWNSTROKE



a. Plunging

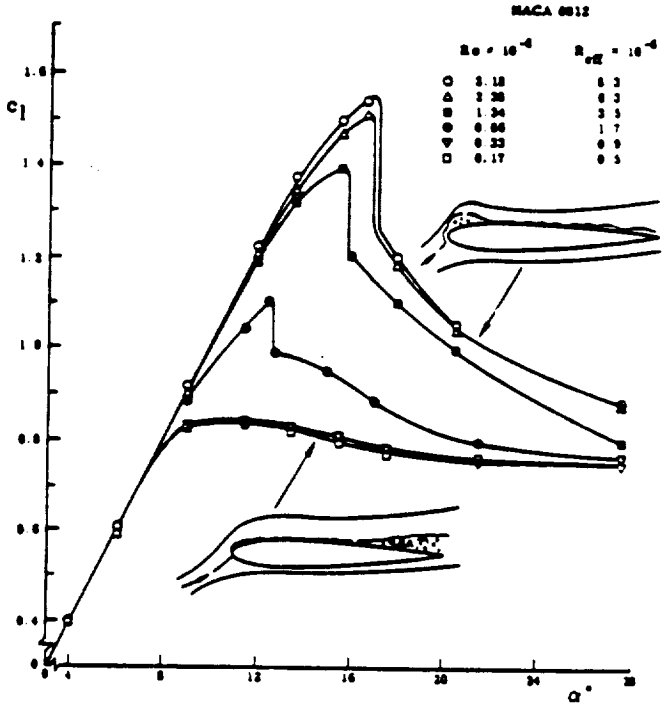


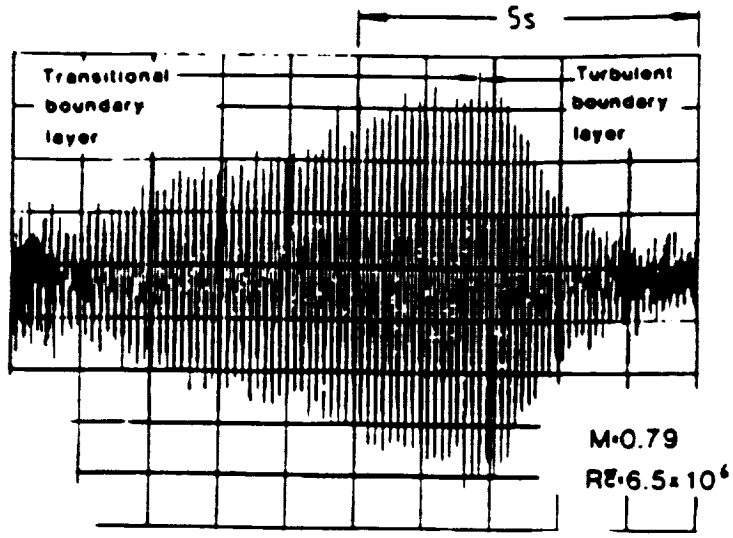
b. Pitching

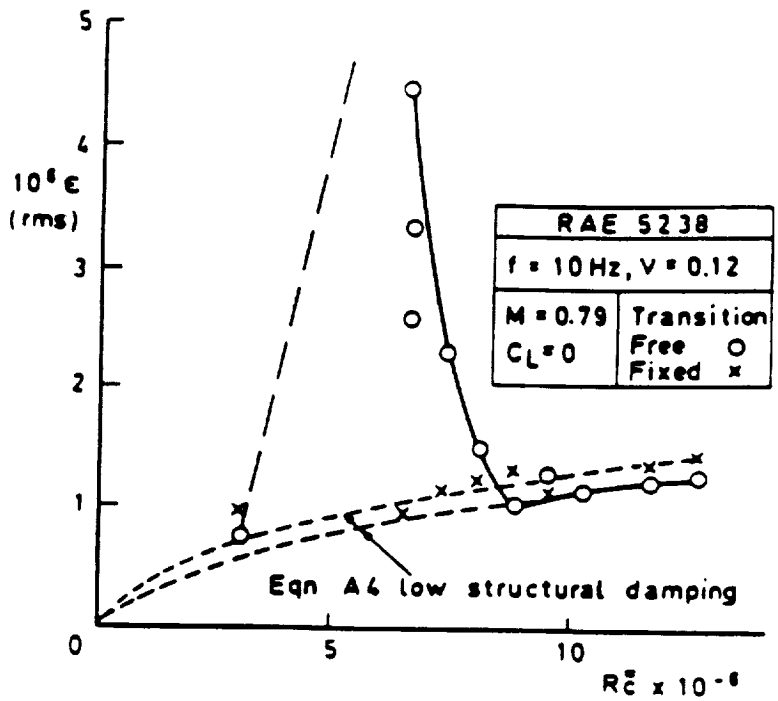


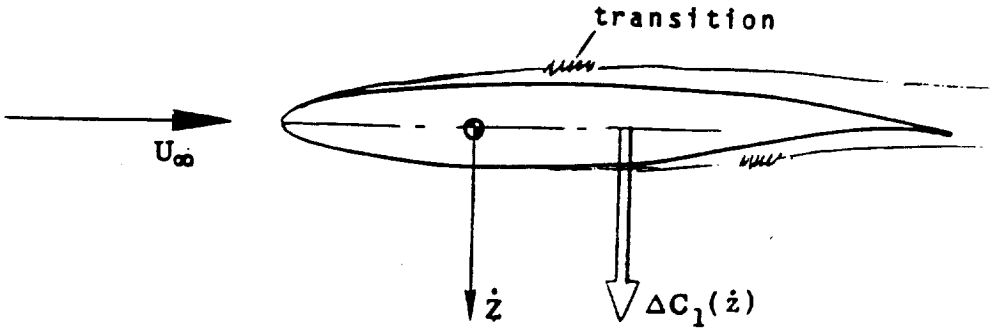
a. Rainey

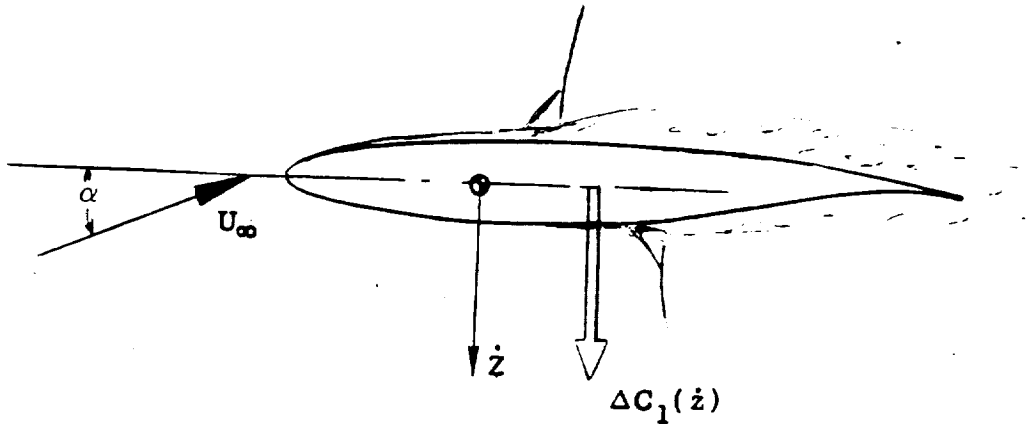
b. Liiva et al

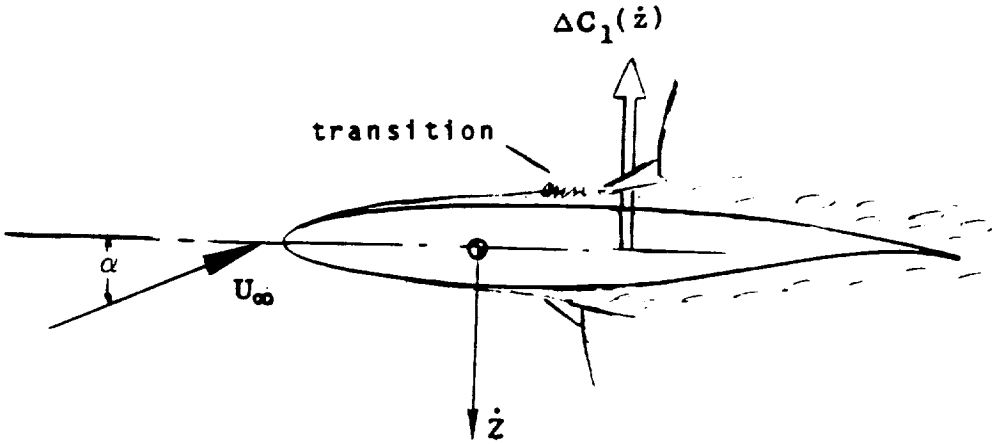


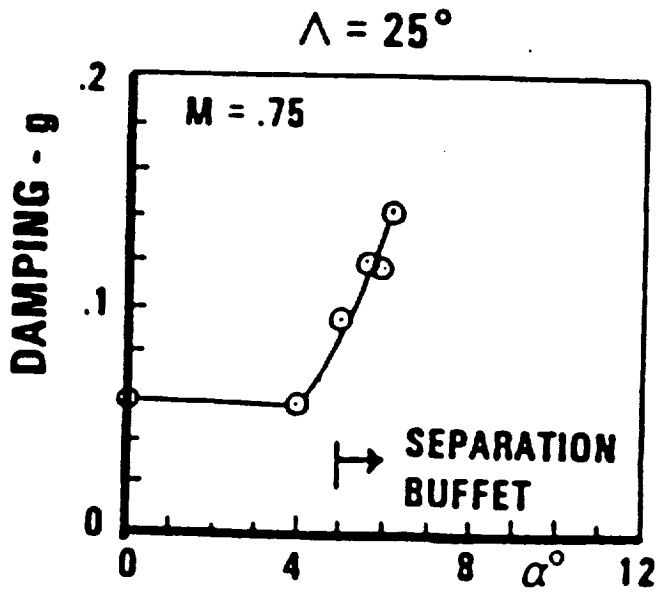

5s
Transitional boundary layer
Turbulent boundary layer
M=0.79
Re=6.5x10^6

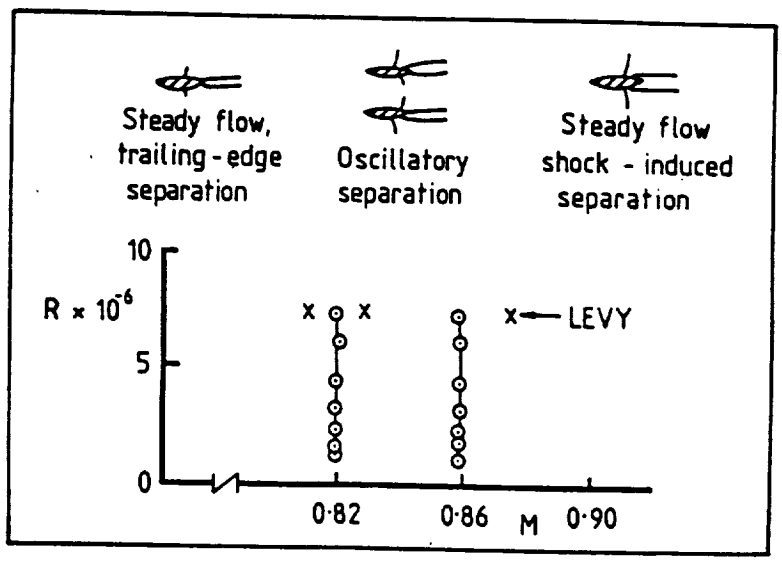

10^6 ε (rms)
RAE 5238
f = 10 Hz, V = 0.12
M = 0.79
C_L = 0
Transition
Free O
Fixed x
Eqn A4 low structural damping
Re x 10^-6
0
1
2
3
4
5
10


transition
U_∞
$\dot{z}$
$\Delta C_l(\dot{z})$

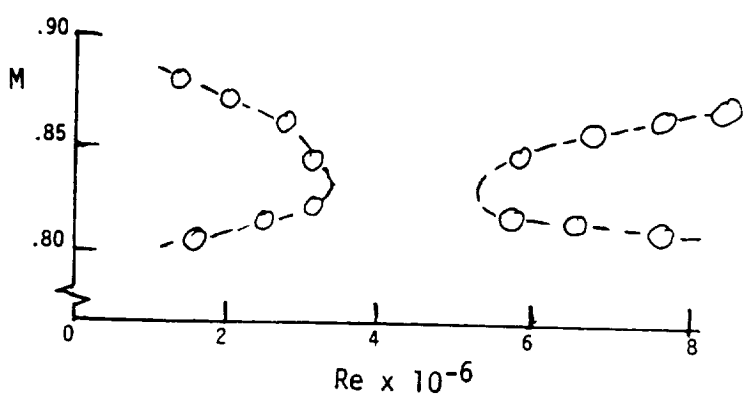

α
U_∞
$\dot{z}$
$\Delta C_l(\dot{z})$

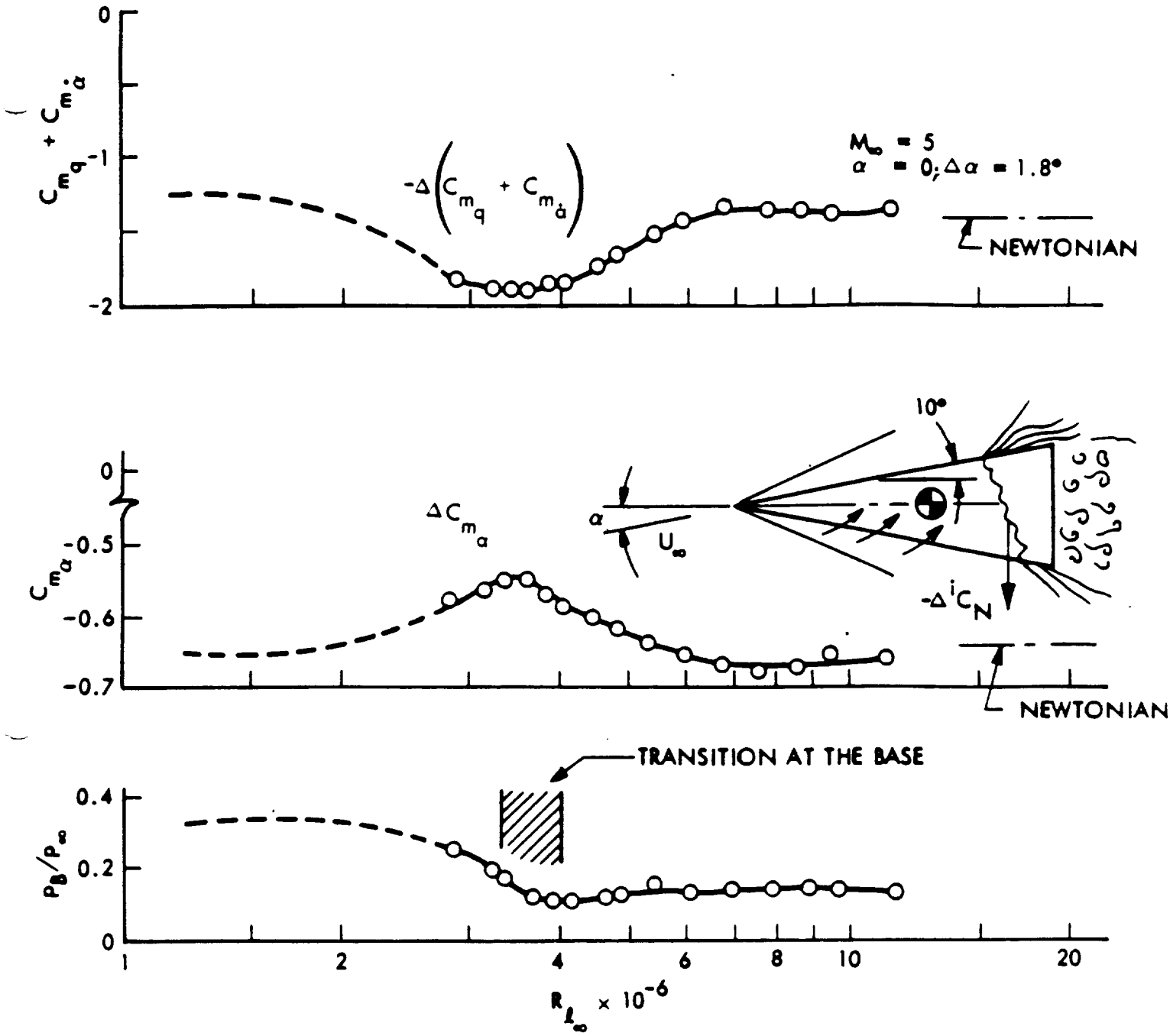

$\Delta C_l(\dot{z})$
transition
α
U_∞
$\dot{z}$

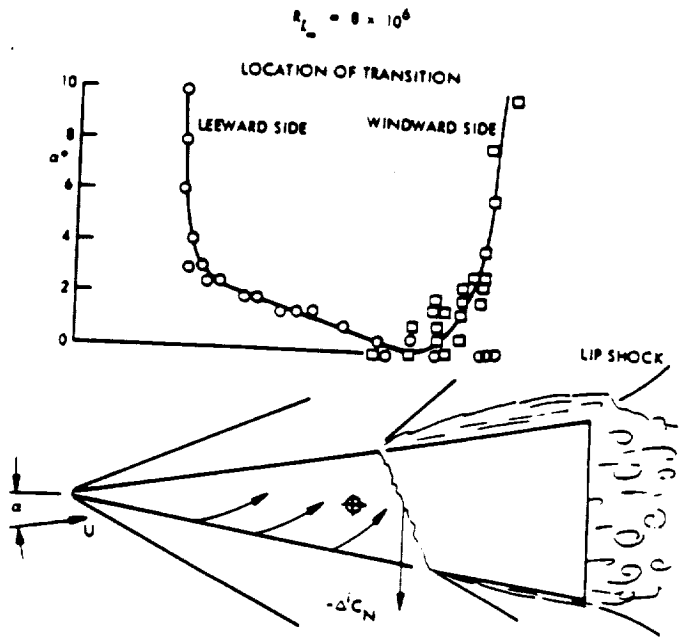


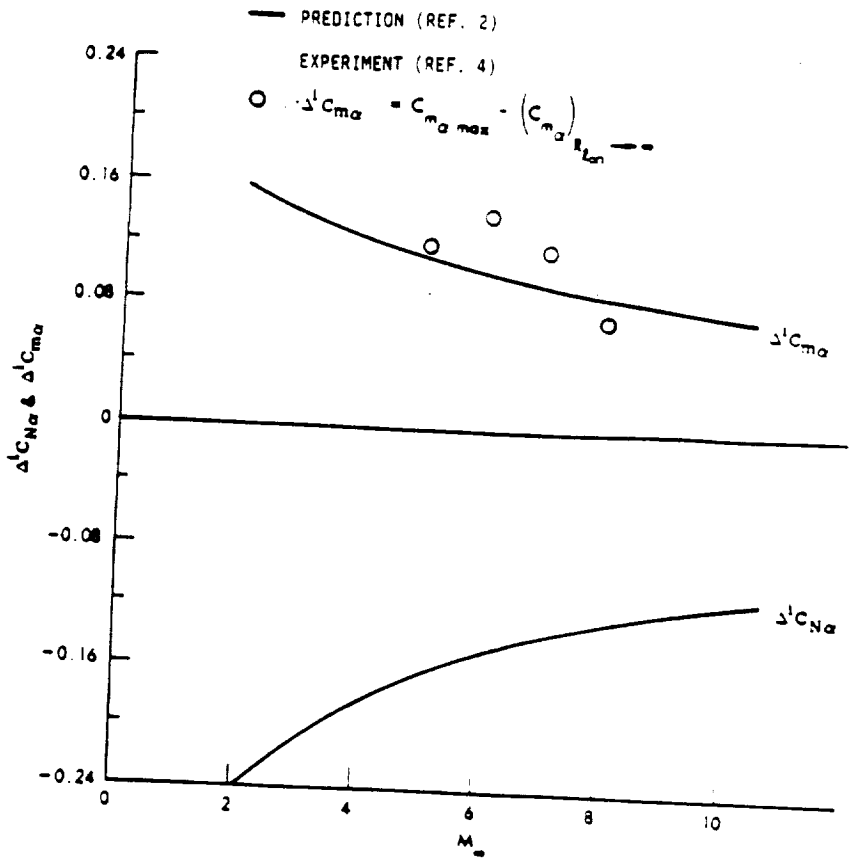


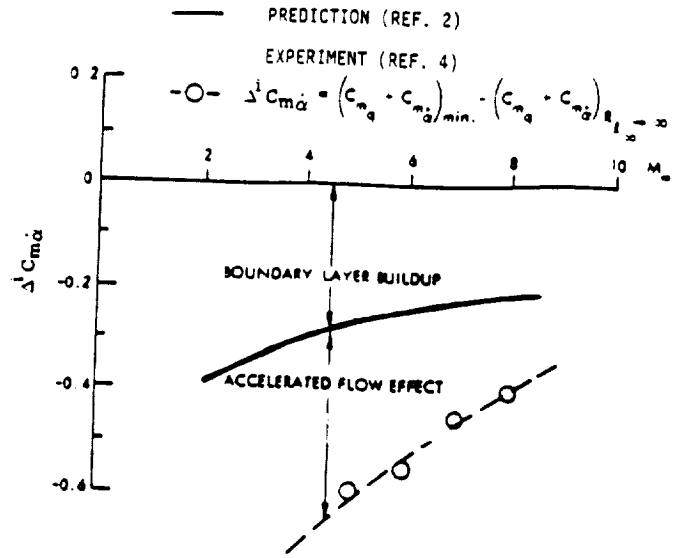
Flow domains for a 14% thick biconvex aerofoil
α = 0°(fixed transition).

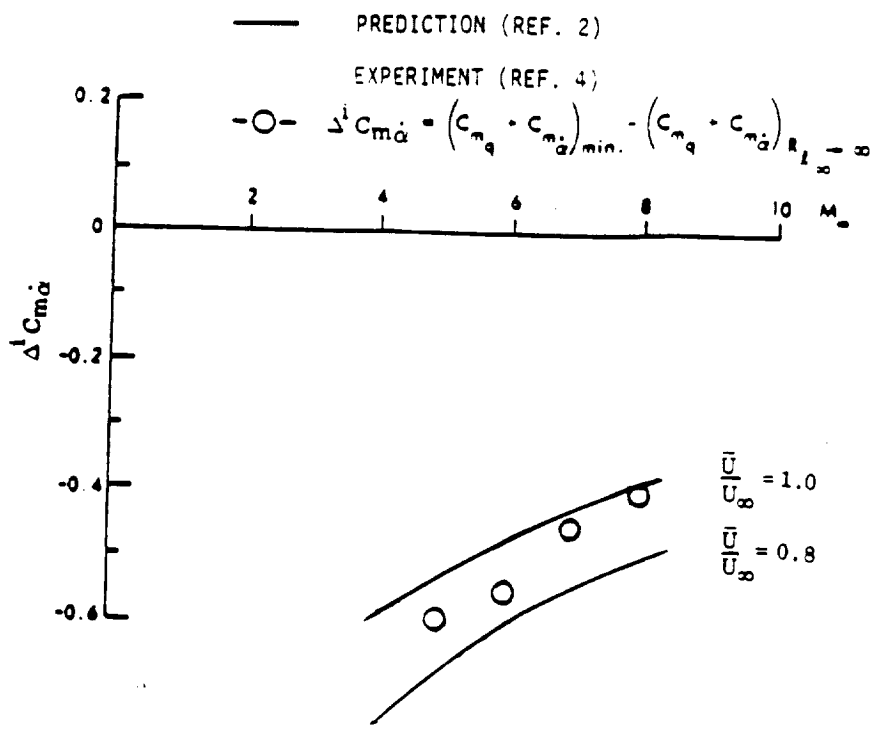


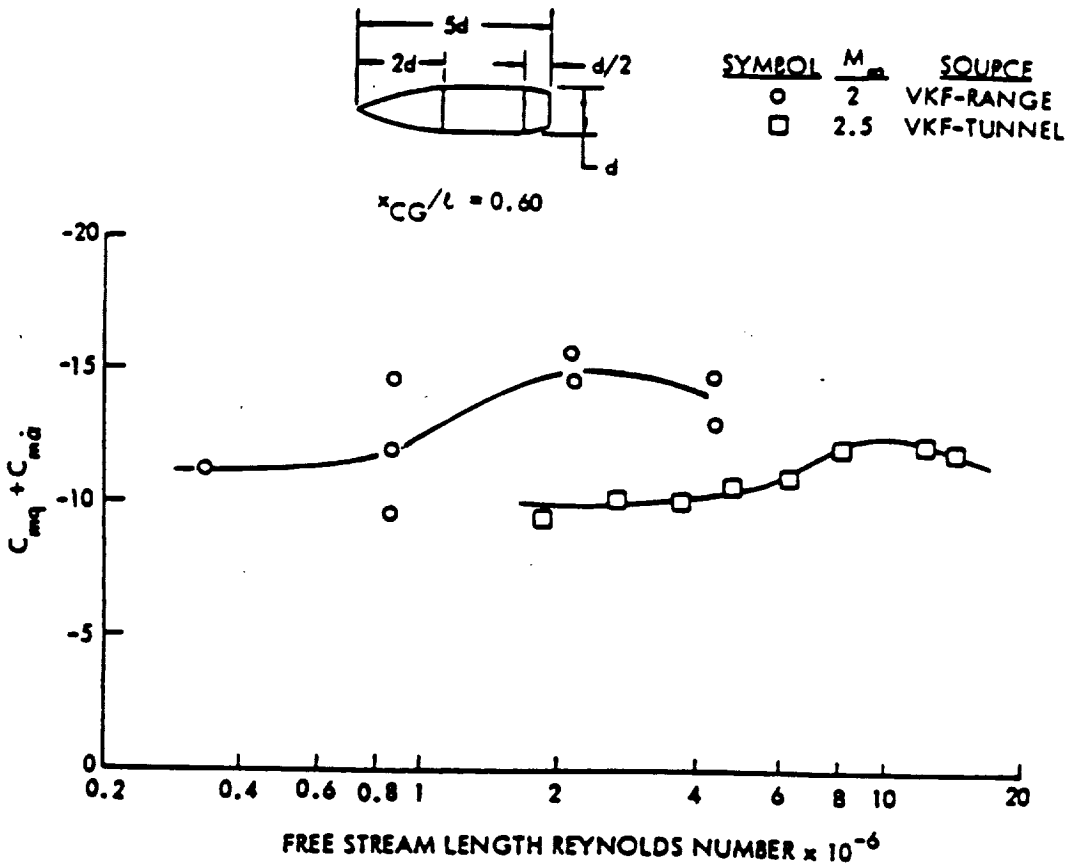

$C_{m_q} + C_{m_{\dot{\alpha}}}$
0
-1
-2
$-\Delta\left(C_{m_q} + C_{m_{\dot{\alpha}}}\right)$
$M_\infty = 5$
$\alpha = 0; \Delta\alpha = 1.8°$
NEWTONIAN
C_{m_α}
0
-0.5
-0.6
-0.7
ΔC_{m_α}
α
U_∞
10°
$-\Delta^i C_N$
NEWTONIAN
TRANSITION AT THE BASE
P_B/P_∞
0.4
0.2
0
1
2
4
6
8
10
20
$R_{\ell_\infty} \times 10^{-6}$

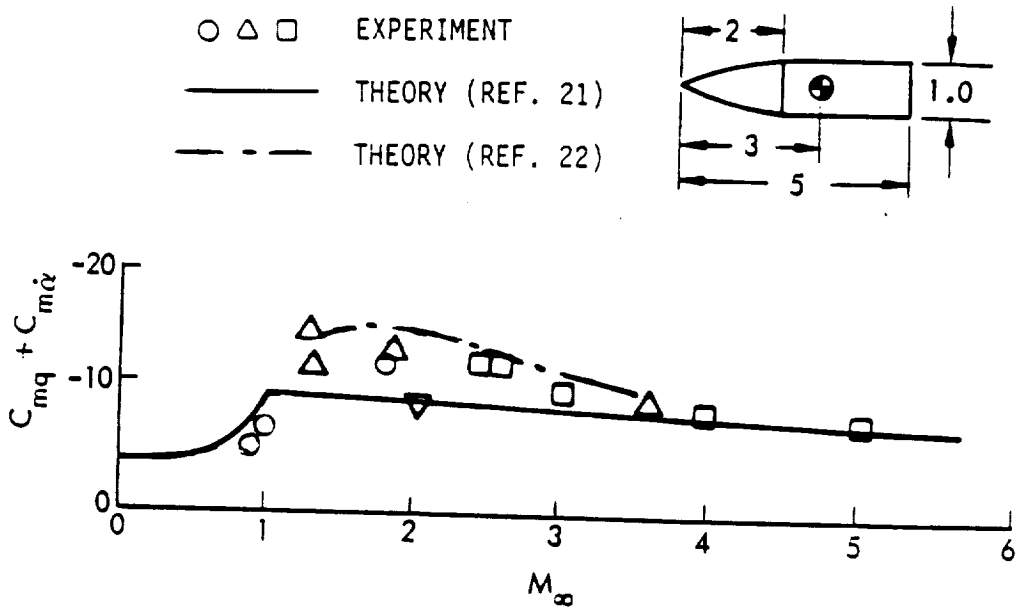

$R_{L_\infty} = 8 \times 10^6$
LOCATION OF TRANSITION
LEEWARD SIDE
WINDWARD SIDE
α°
10
8
6
4
2
0
LIP SHOCK
α
U
$-\Delta^1 C_N$

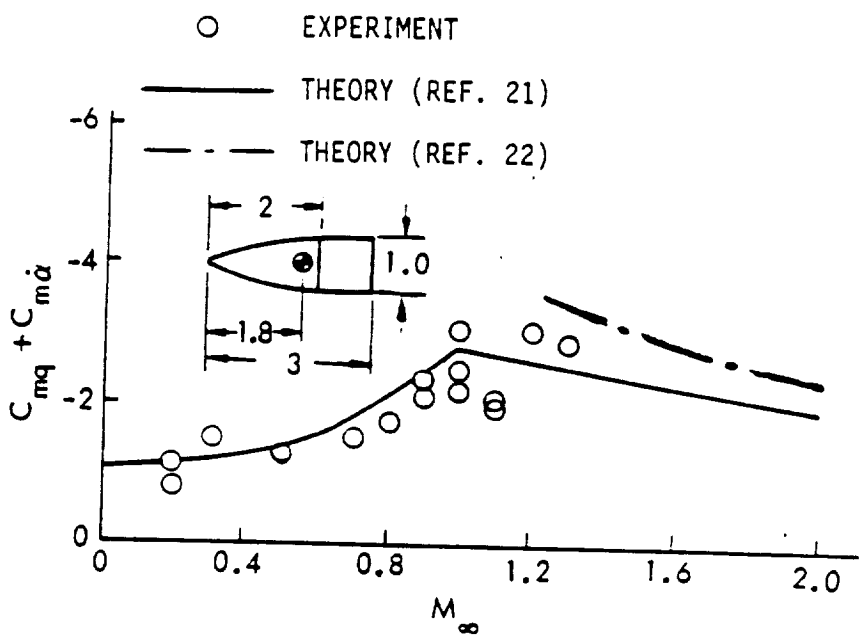

PREDICTION (REF. 2)
EXPERIMENT (REF. 4)
$\Delta^1 C_{m\alpha} = C_{m_{\alpha\,max}} - \left(C_{m_\alpha}\right)_{R_{L_\infty} \to \infty}$
$\Delta^1 C_{m\alpha}$
$\Delta^1 C_{N\alpha}$
$\Delta^1 C_{N\alpha}$ & $\Delta^1 C_{m\alpha}$
0.24
0.16
0.08
0
-0.08
-0.16
-0.24
0
2
4
6
8
10
M_∞

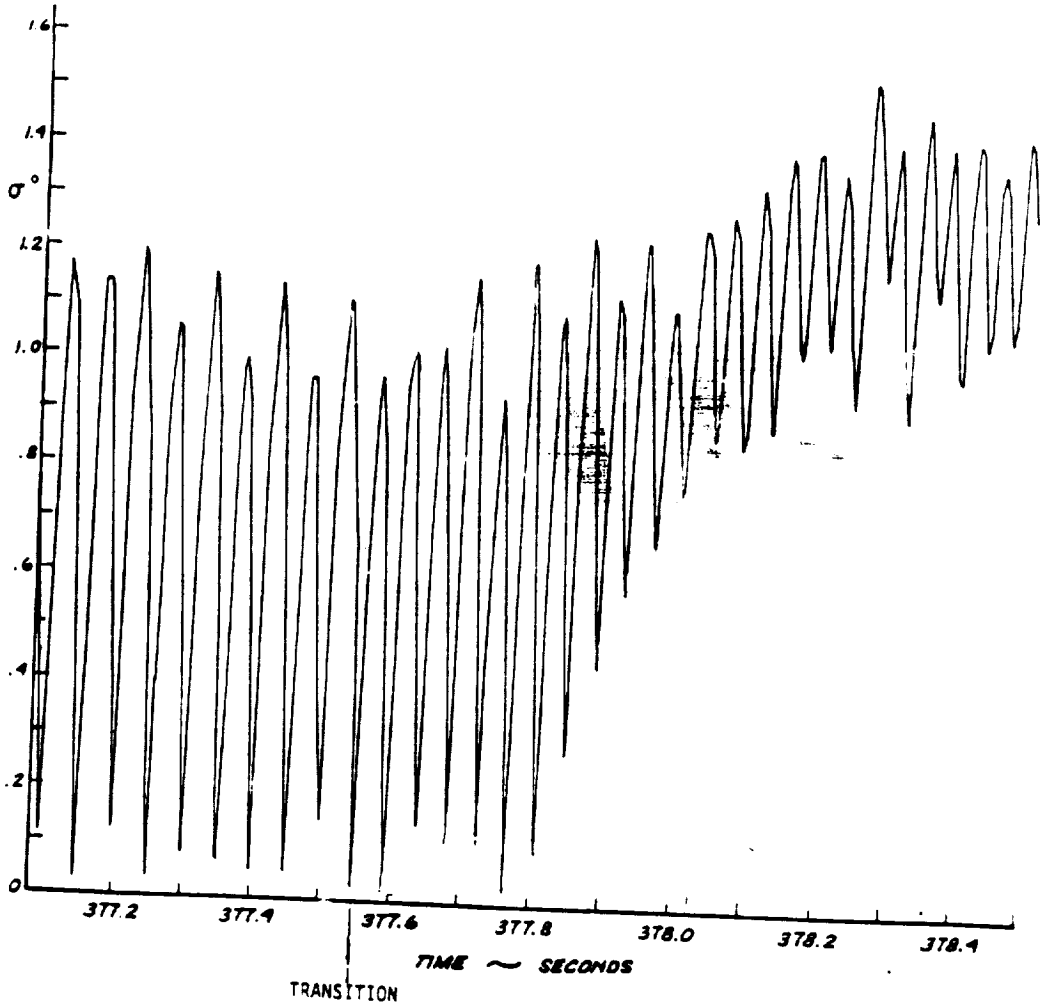

PREDICTION (REF. 2)
EXPERIMENT (REF. 4)
$\Delta^i C_{m\dot{\alpha}} = \left(C_{m_q} + C_{m_{\dot{\alpha}}}\right)_{min.} - \left(C_{m_q} + C_{m_{\dot{\alpha}}}\right)_{R_{L_\infty} \to \infty}$
0.2
0
-0.2
-0.4
-0.6
$\Delta^i C_{m\dot{\alpha}}$
2
4
6
8
10
M_∞
BOUNDARY LAYER BUILDUP
ACCELERATED FLOW EFFECT

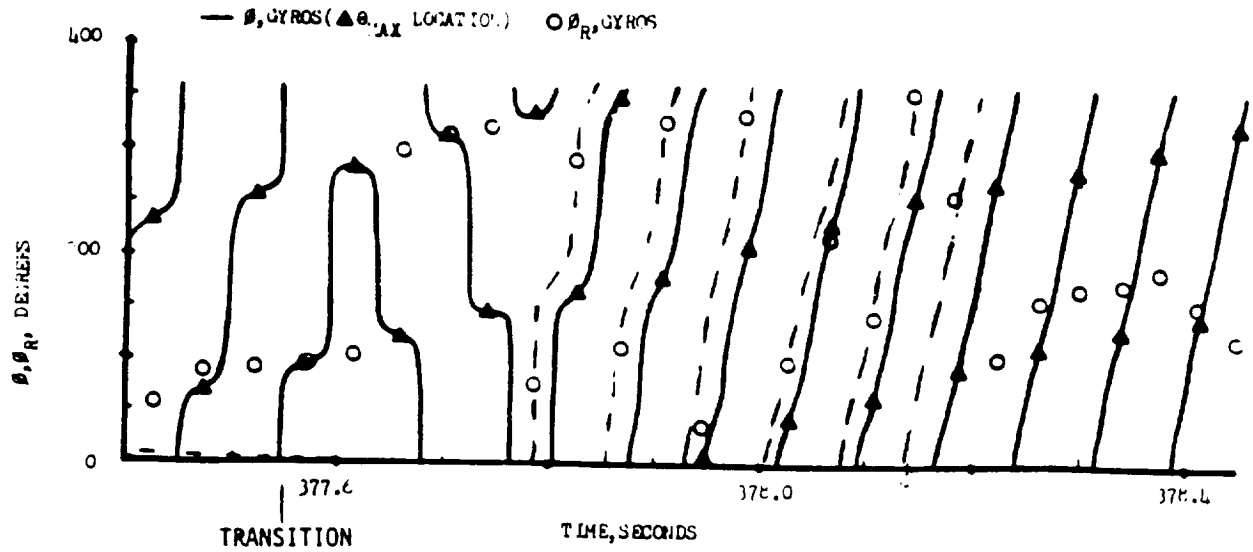

PREDICTION (REF. 2)
EXPERIMENT (REF. 4)
$\Delta^i C_{m\dot{\alpha}} = \left(C_{m_q} + C_{m_{\dot{\alpha}}}\right)_{min.} - \left(C_{m_q} + C_{m_{\dot{\alpha}}}\right)_{R_{L_\infty} \to \infty}$
0.2
0
-0.2
-0.4
-0.6
$\Delta^i C_{m\dot{\alpha}}$
2
4
6
8
10
M_∞
$\frac{\bar{U}}{U_\infty} = 1.0$
$\frac{\bar{U}}{U_\infty} = 0.8$

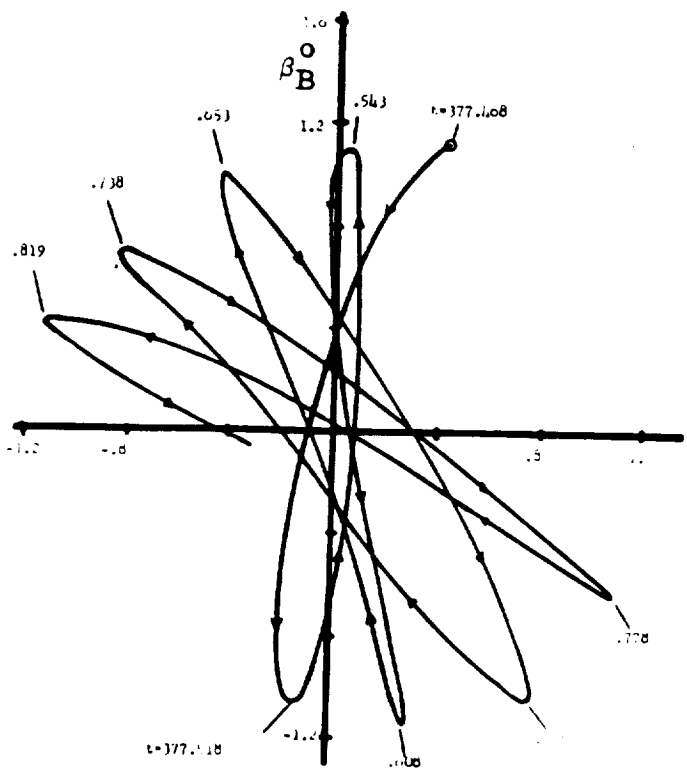

5d
2d
d/2
d
SYMBOL
M_∞
SOURCE
2
VKF-RANGE
2.5
VKF-TUNNEL
$x_{CG}/\ell = 0.60$
-20
-15
-10
-5
0
$C_{mq} + C_{m\dot{\alpha}}$
0.2
0.4
0.6
0.8
1
2
4
6
8
10
20
FREE STREAM LENGTH REYNOLDS NUMBER x 10^{-6}


EXPERIMENT
THEORY (REF. 21)
THEORY (REF. 22)
2
1.0
3
5
$C_{mq} + C_{m\dot{\alpha}}$
-20
-10
0
0
1
2
3
4
5
6
M_∞

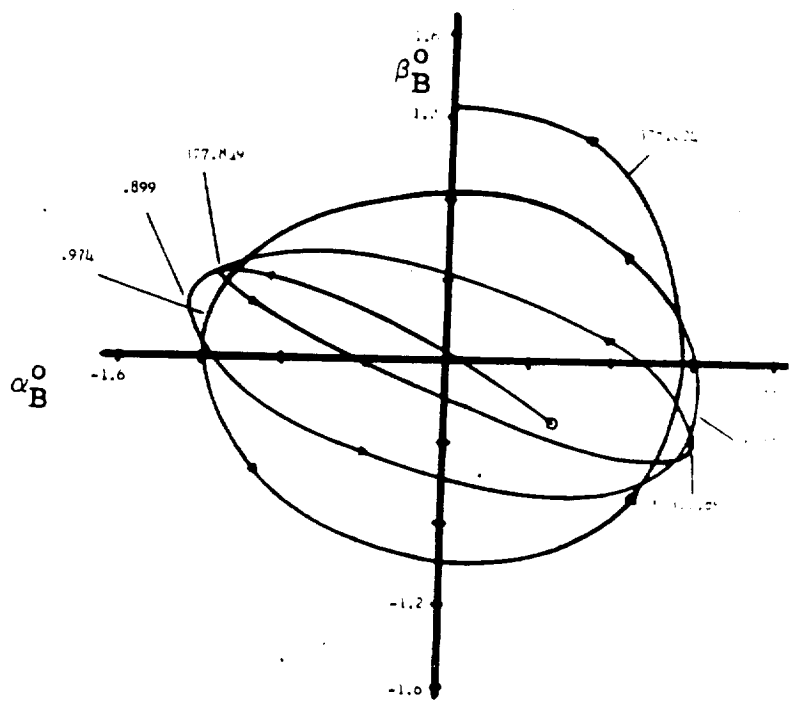

EXPERIMENT
THEORY (REF. 21)
THEORY (REF. 22)
2
1.0
1.8
3
$C_{mq} + C_{m\dot{\alpha}}$
-6
-4
-2
0
0
0.4
0.8
1.2
1.6
2.0
M_∞


1.6
1.4
σ°
1.2
1.0
.8
.6
.4
.2
0
377.2
377.4
377.6
377.8
378.0
378.2
378.4
TIME ~ SECONDS
TRANSITION

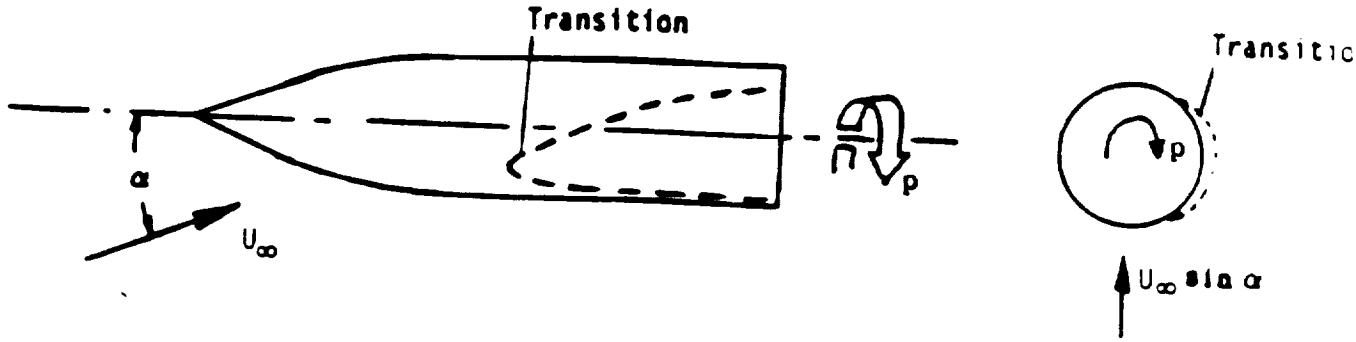




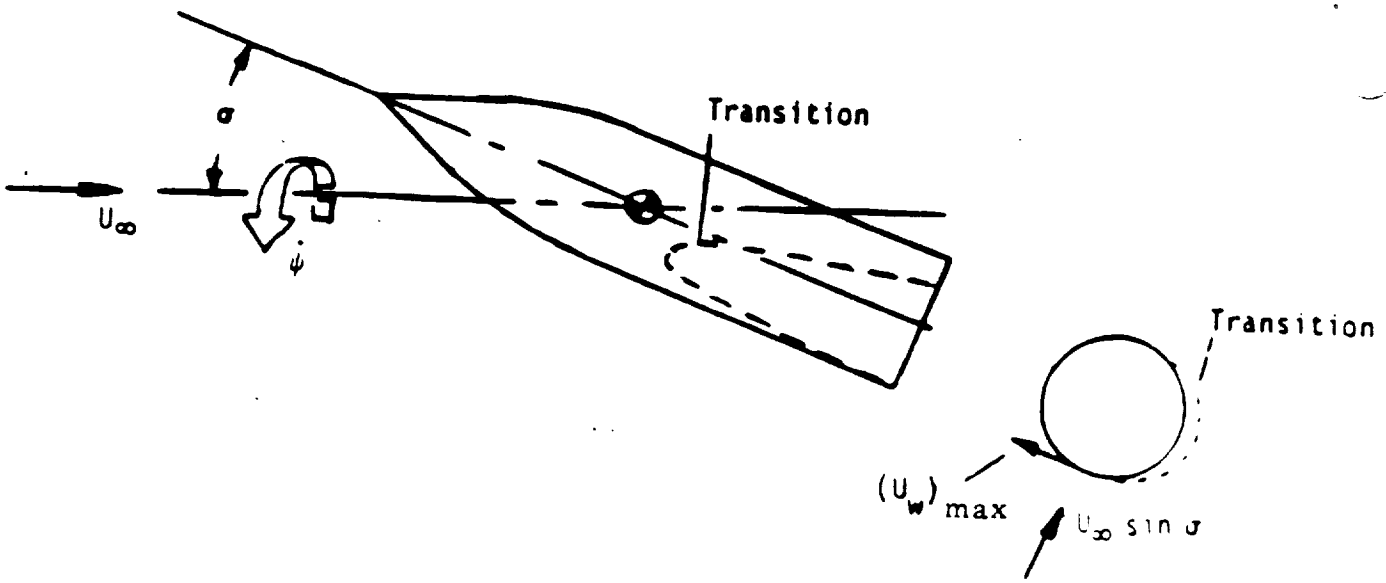
BEFORE TRANSITION



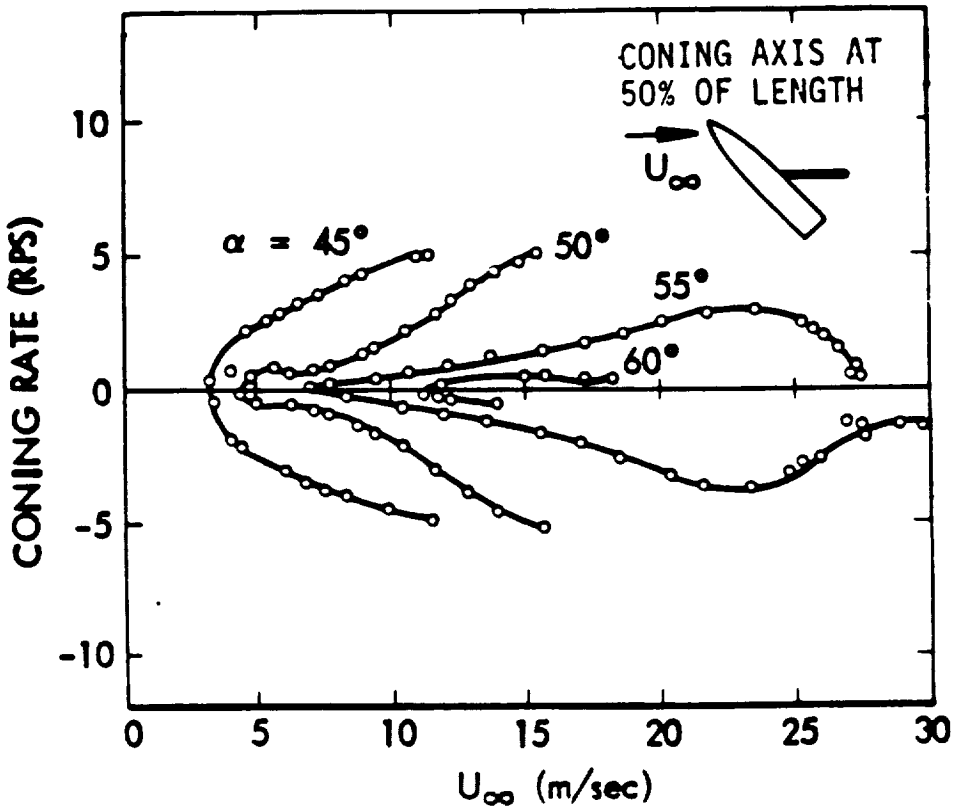
AFTER TRANSITION



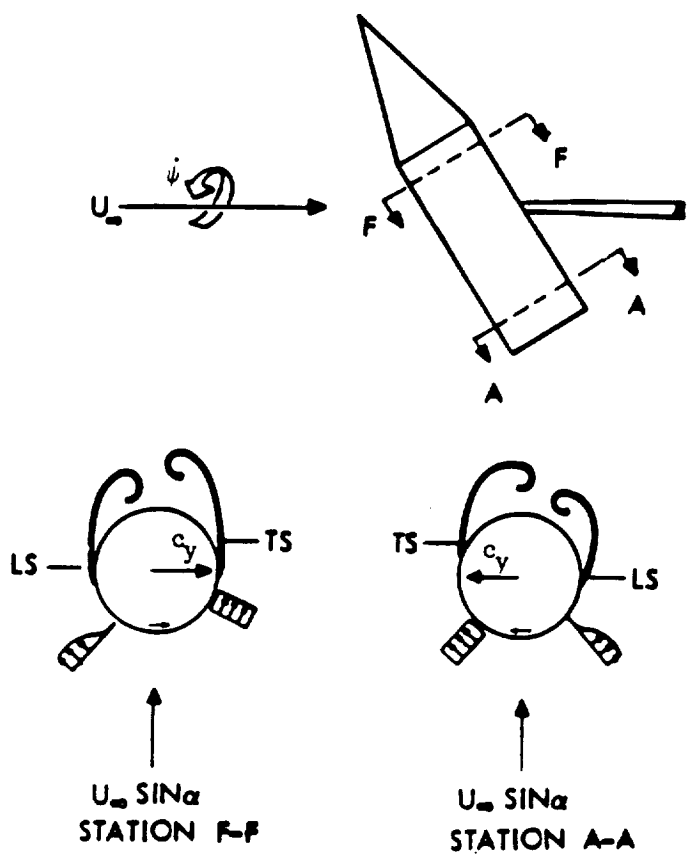
a. Spinning body

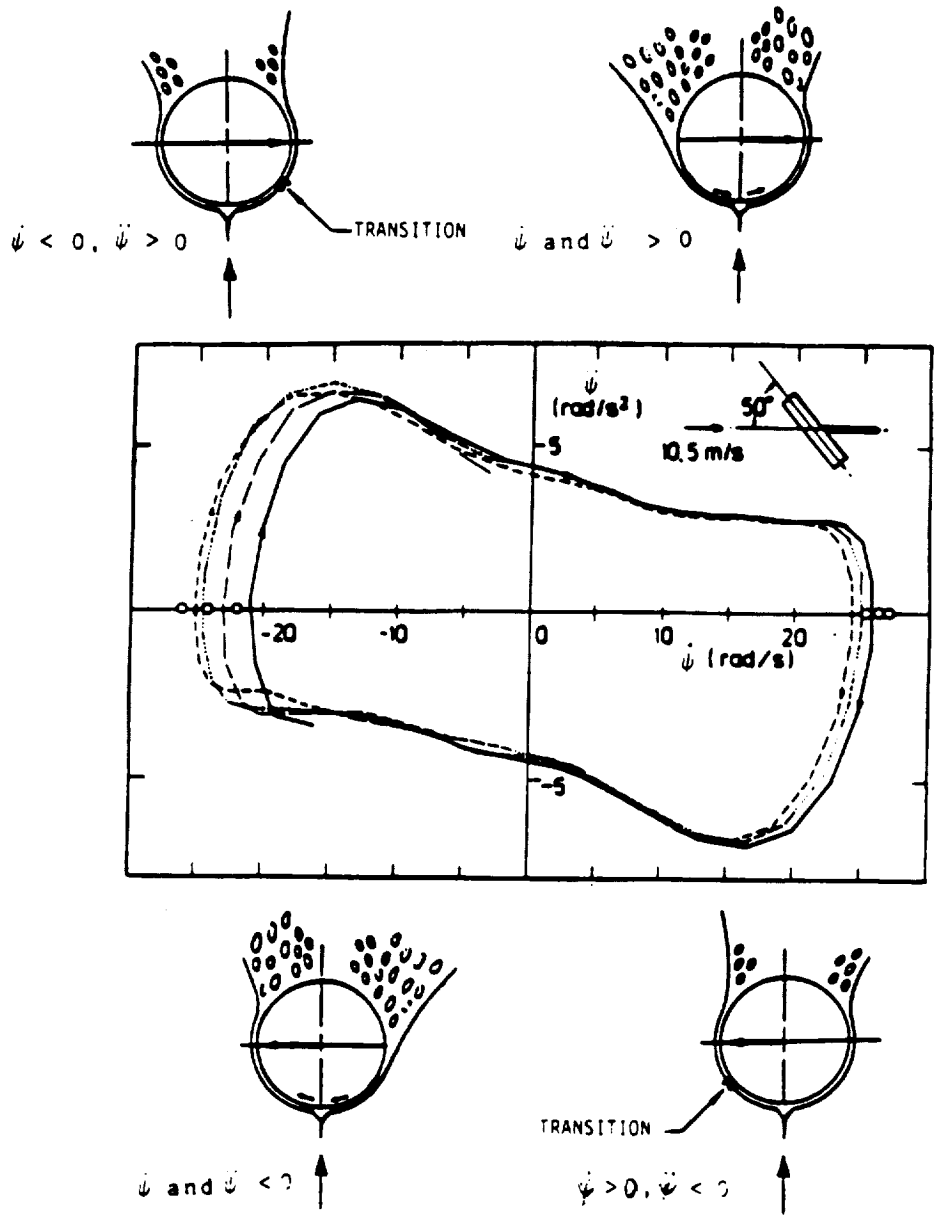


b. Coning body

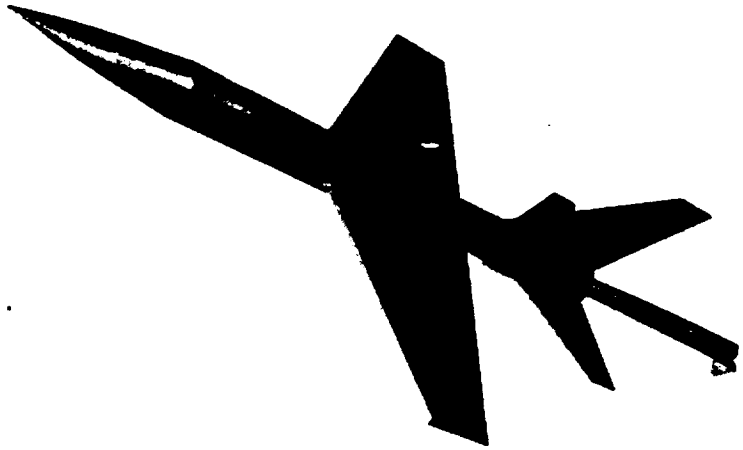


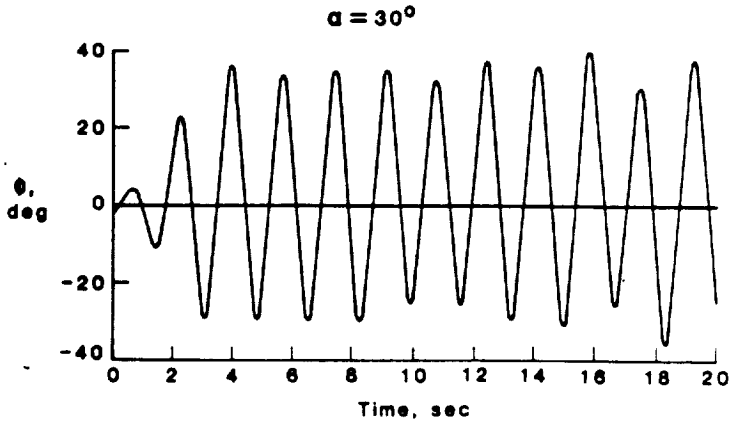
Dual coning characteristics of a cone-cylinder

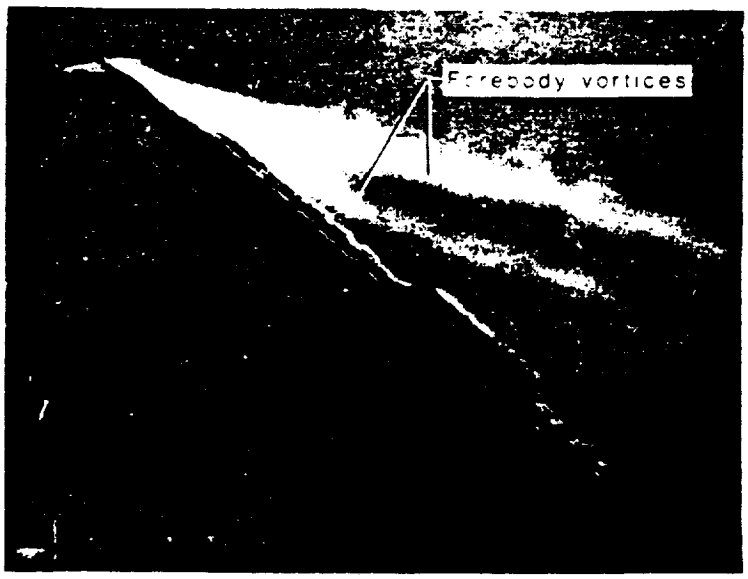




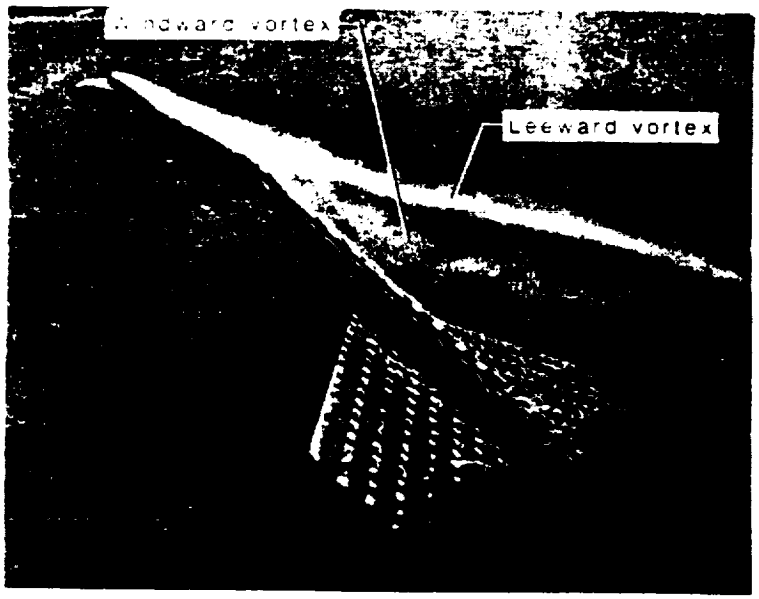
Reversal of cylinder coning motion



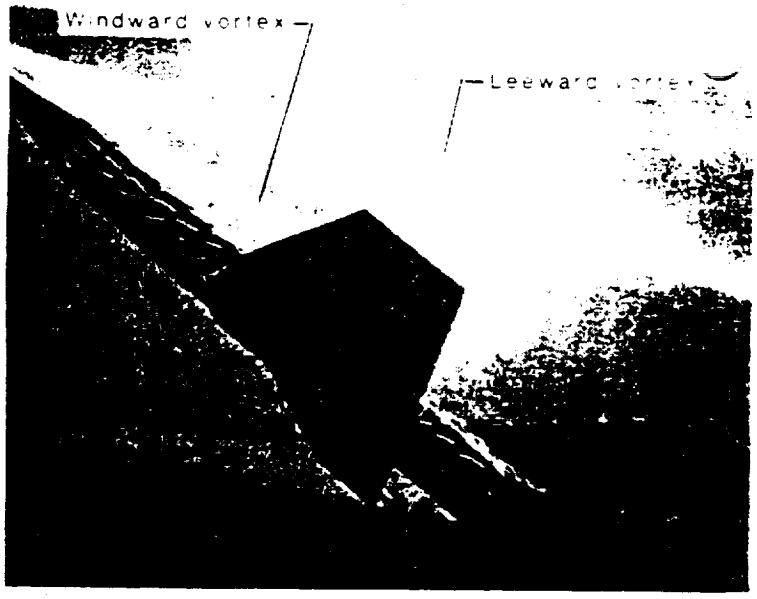

α = 30°
40
20
0
-20
-40
ϕ, deg
0
2
4
6
8
10
12
14
16
18
20
Time, sec



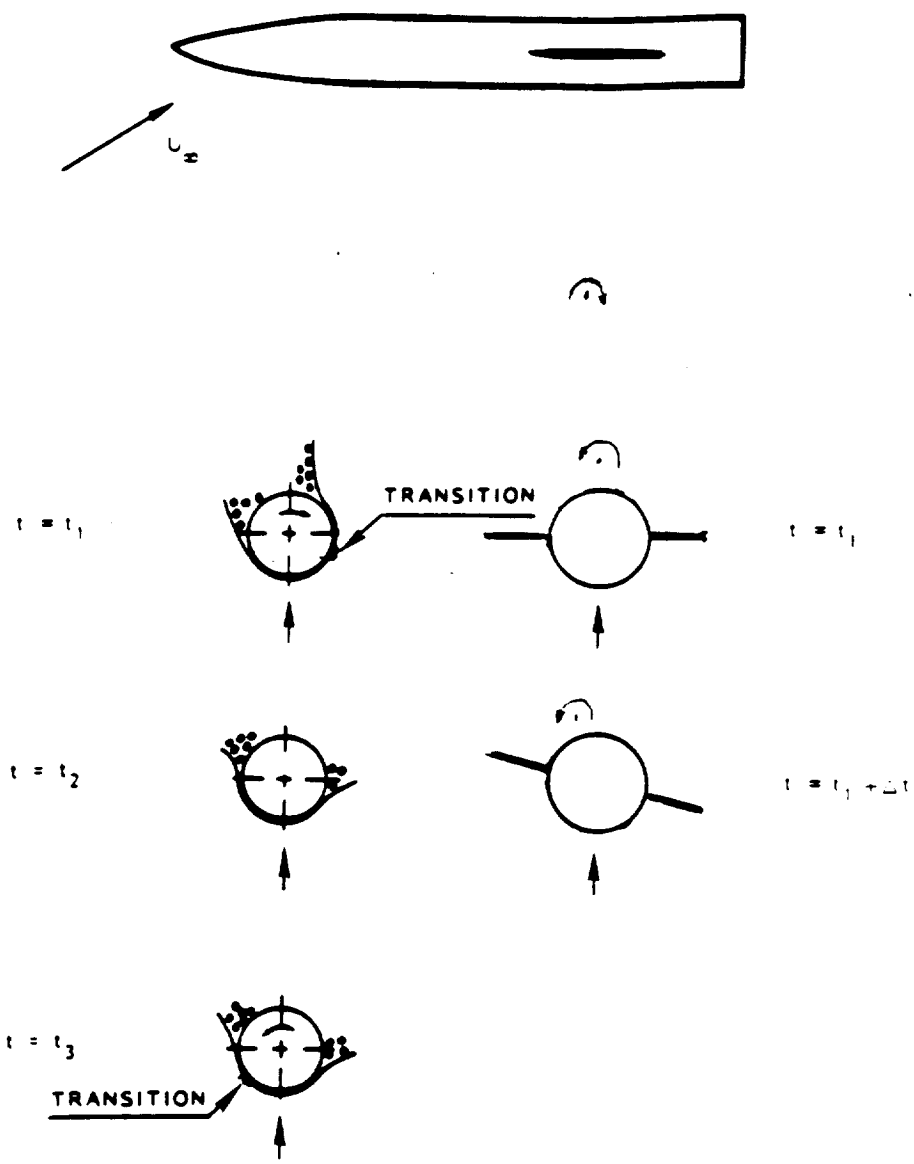
(b) Model rolling through wing-level position.



(a) Model at left wing down roll angle.



(c) Model at right wing down roll angle.


U_∞
TRANSITION
$t = t_1$
$t = t_1$
$t = t_2$
$t = t_1 + \Delta t$
$t = t_3$
TRANSITION

CFD VALIDATION EXPERIMENTS AT UTRC

William P. Patrick

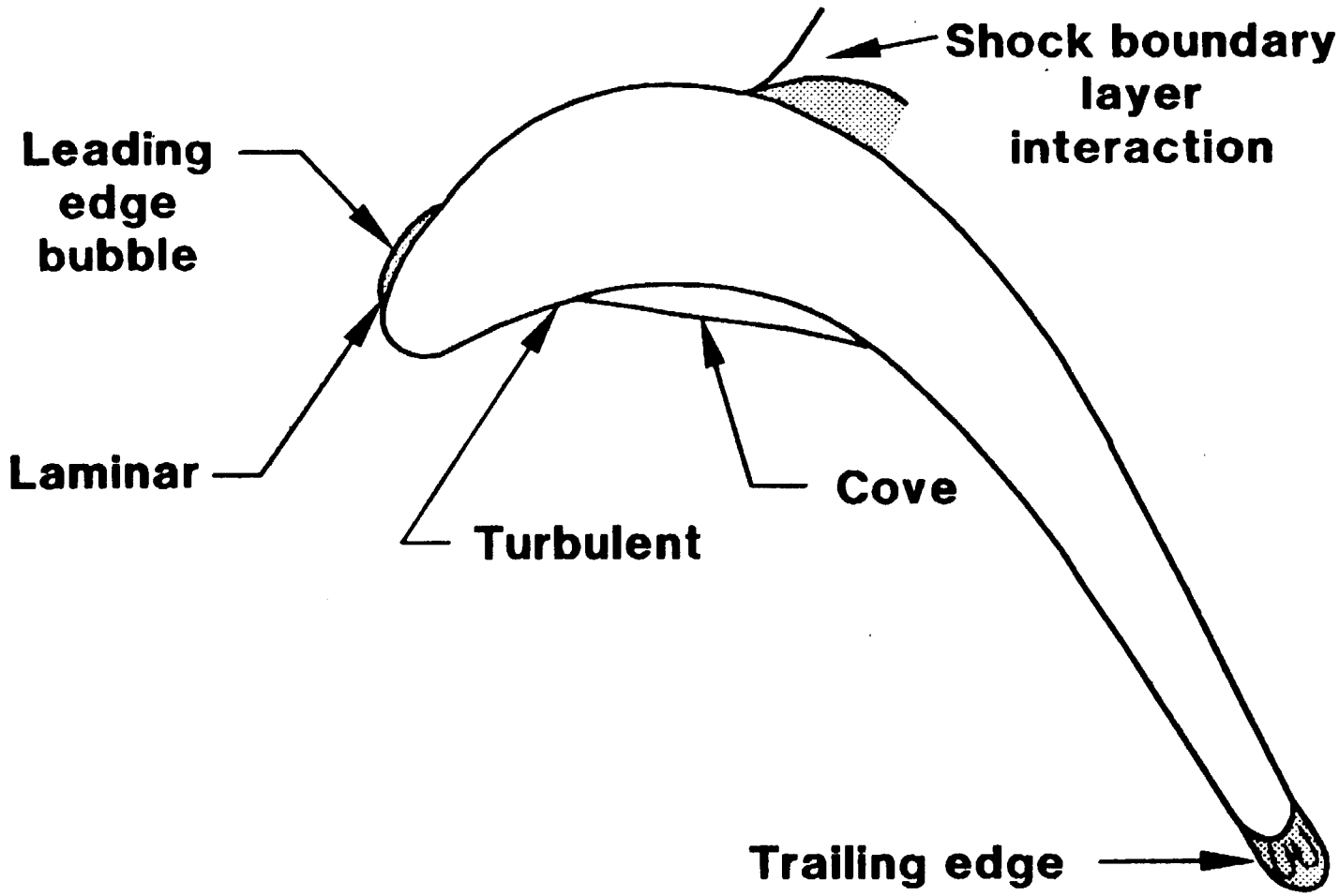
NASA CFD Validation Workshop
Ames Research Center
July 14-16, 1987

UNITED TECHNOLOGIES RESEARCH CENTER

N92-70948

RA2249TX.008

AIRFOIL SURFACE SEPARATION

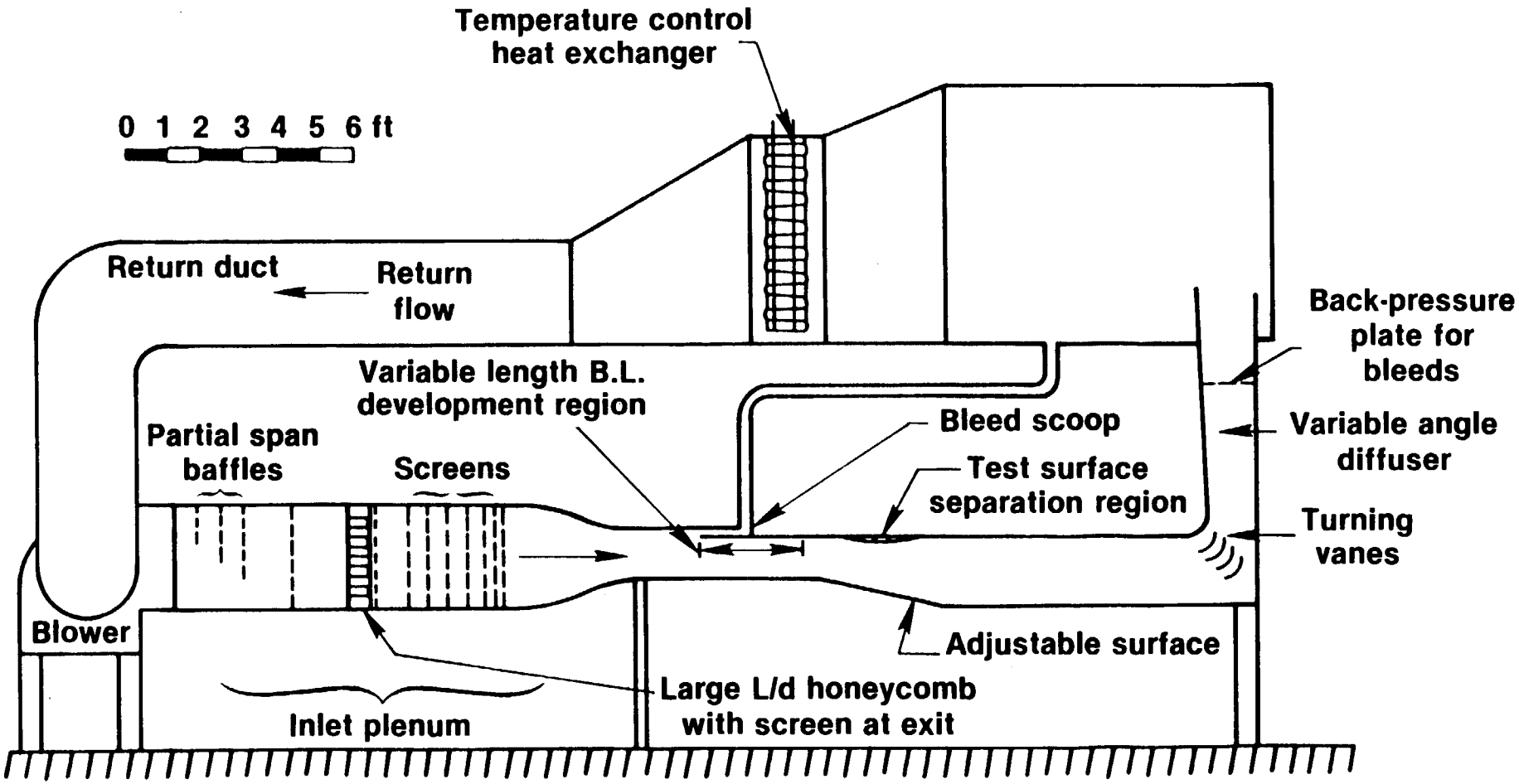


METHOD OF APPROACH

- Create large scale, two-dimensional separation bubble on flat plate
- Use low speed, low turbulence facility
- Obtain extensive data set using non-intrusive laser velocimetry in addition to wall static pressure, total pressure, and hot-film measurements

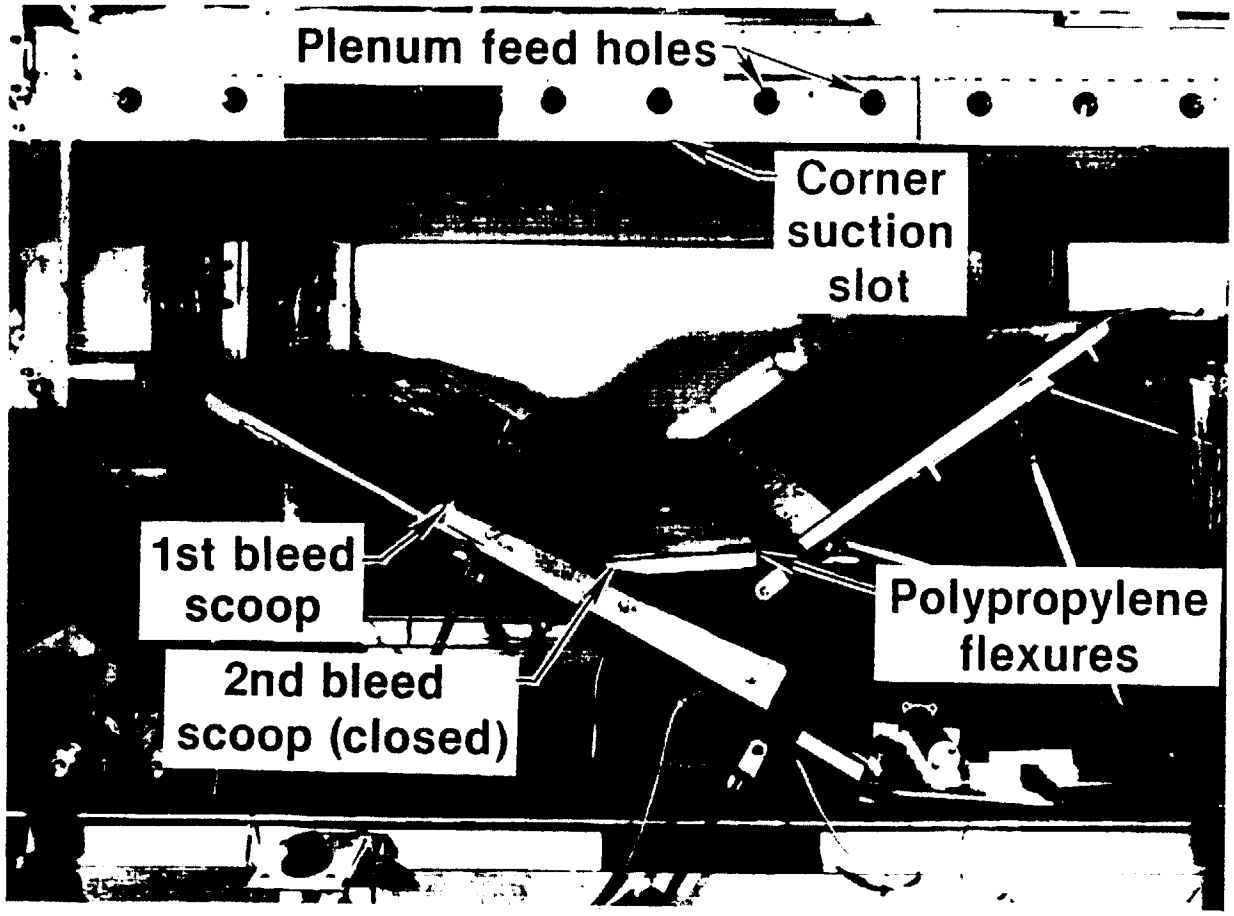
RE660TX.002

UTRC BOUNDARY LAYER WIND TUNNEL



85-6-45-5

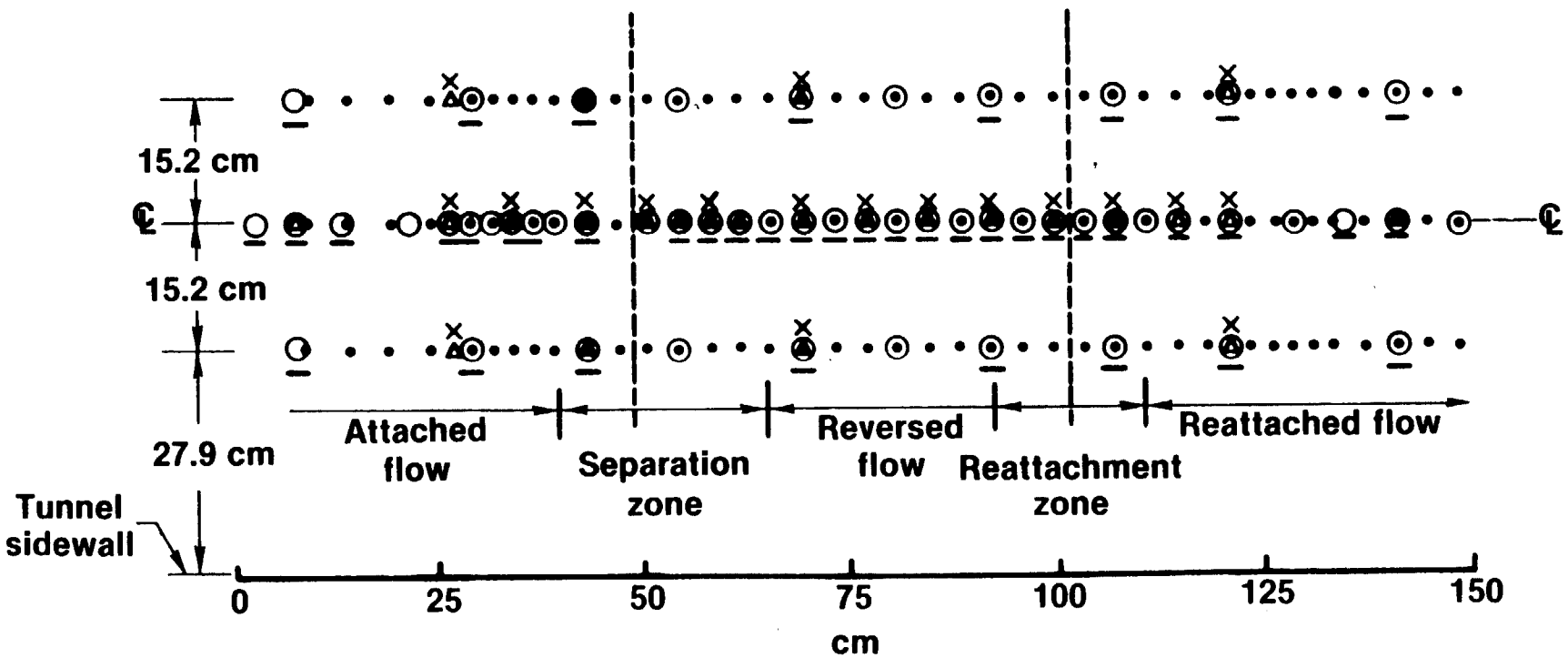
TURBULENT BOUNDARY LAYER SEPARATION TEST SECTION



85-6-85-16

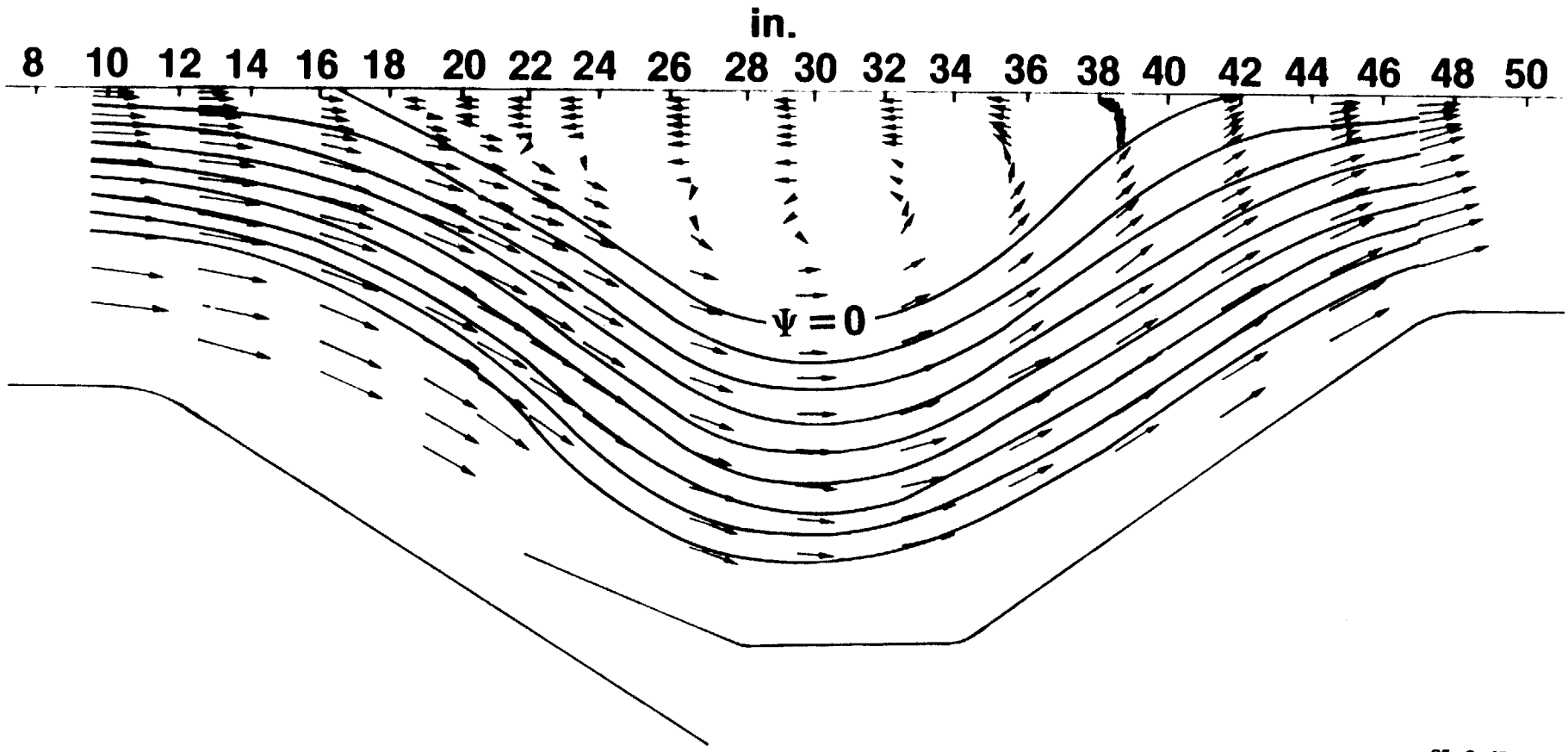
MEASUREMENT LOCATIONS ON TEST PLATE

• Static pressure (120 taps)
○ Total pressure (54)*
△ LV (velocity) (25)*
× LV (Reynolds stress) (20)*
– Hot-film (45)*
*Number of traverse locations on test plate



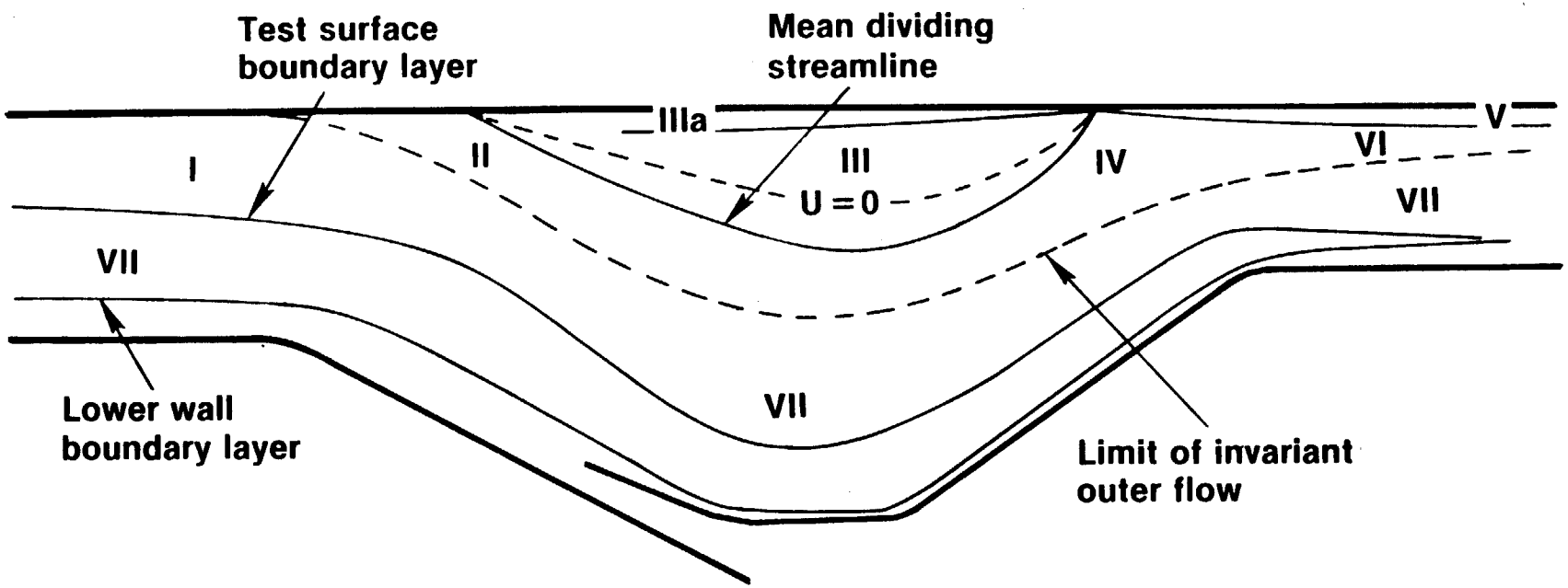
85–6–85–2

STREAMLINES DETERMINED FROM FLOW VELOCITIES MEASURED WITH LASER VELOCIMETER



85-6-45-8

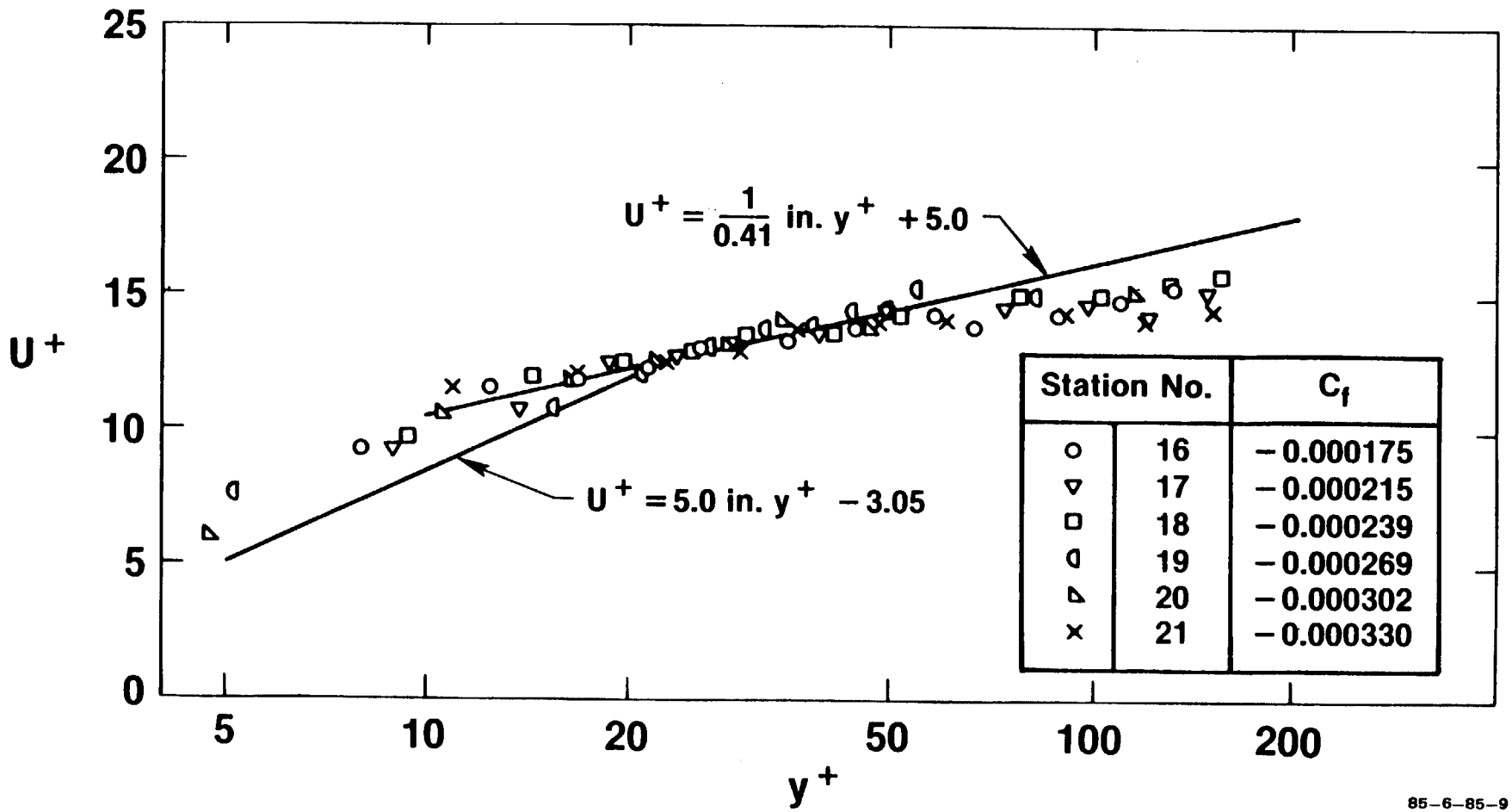
SEPARATION BUBBLE FLOW ZONES



I Attached flow
II Intermittent separation
III Separation bubble
IIIa Backflow boundary layer
IV Reattachment zone
V Redeveloping near wall flow
VI Relaxing outer shear layer
VII Invariant outer flowfield

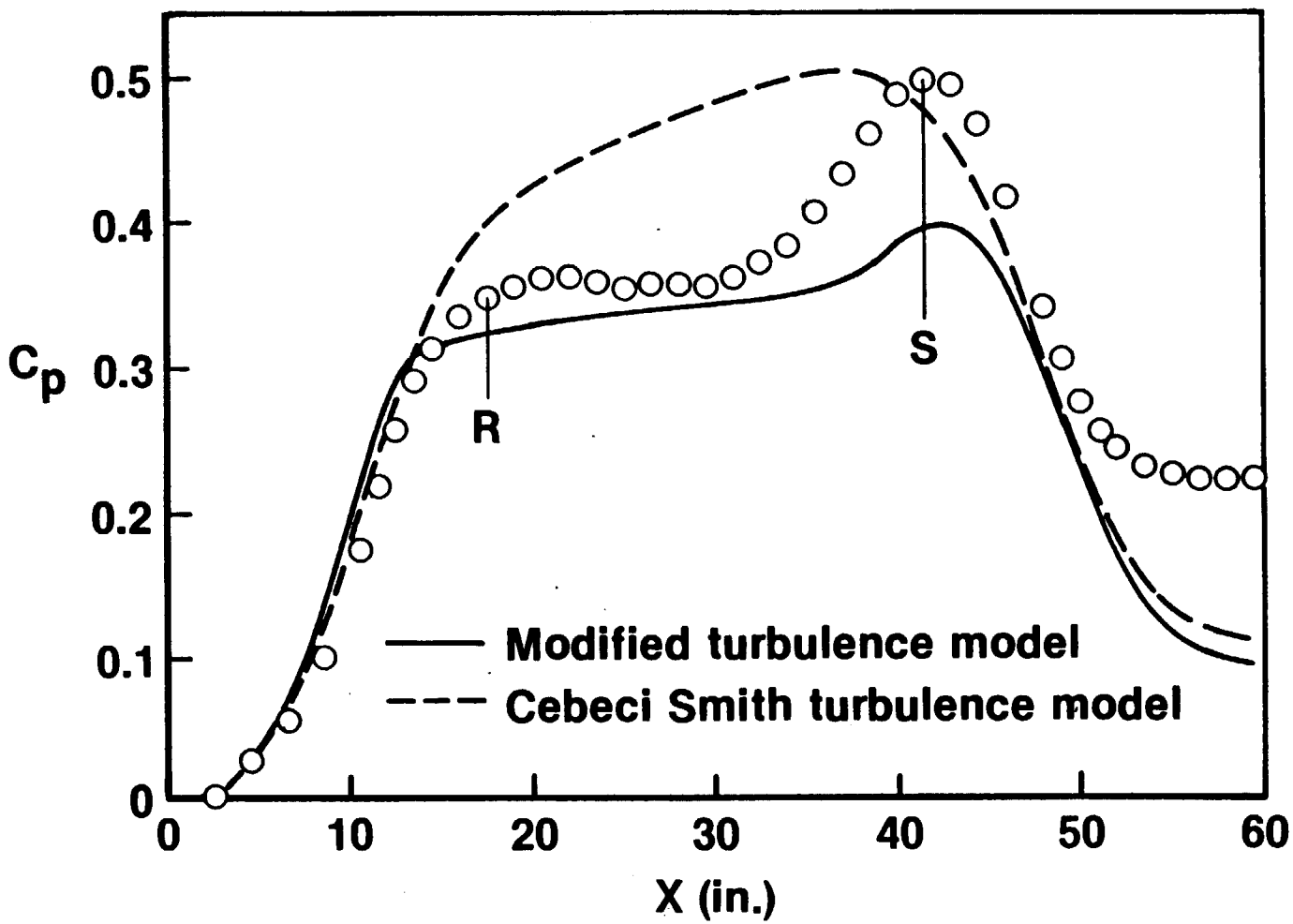
85-6-85-13

BACKFLOW VELOCITY PROFILES PLOTTED IN LAW-OF-THE-WALL COORDINATES



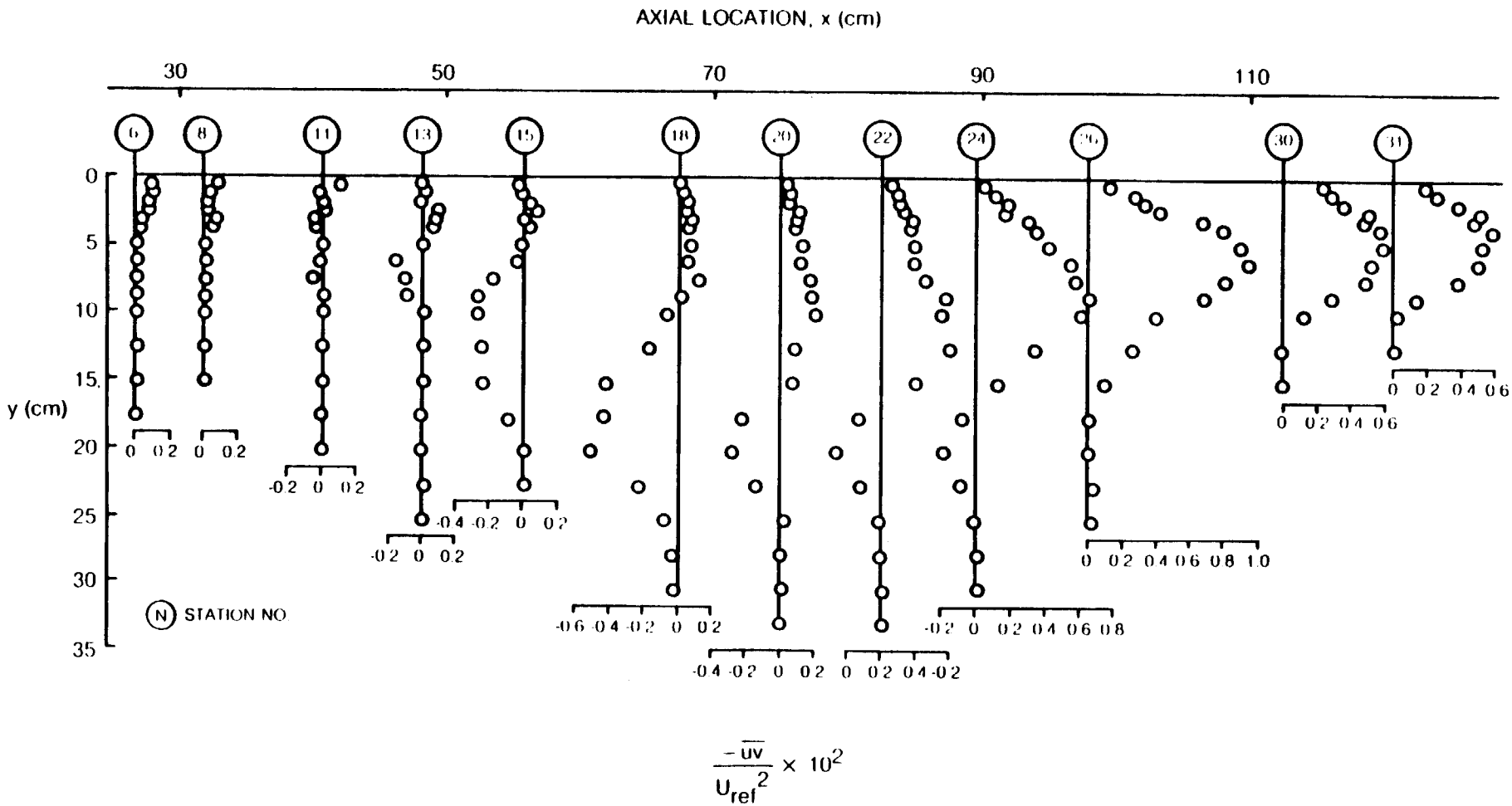
85–6–85–9

COMPARISON OF IBL SURFACE PRESSURE WITH EXPERIMENT

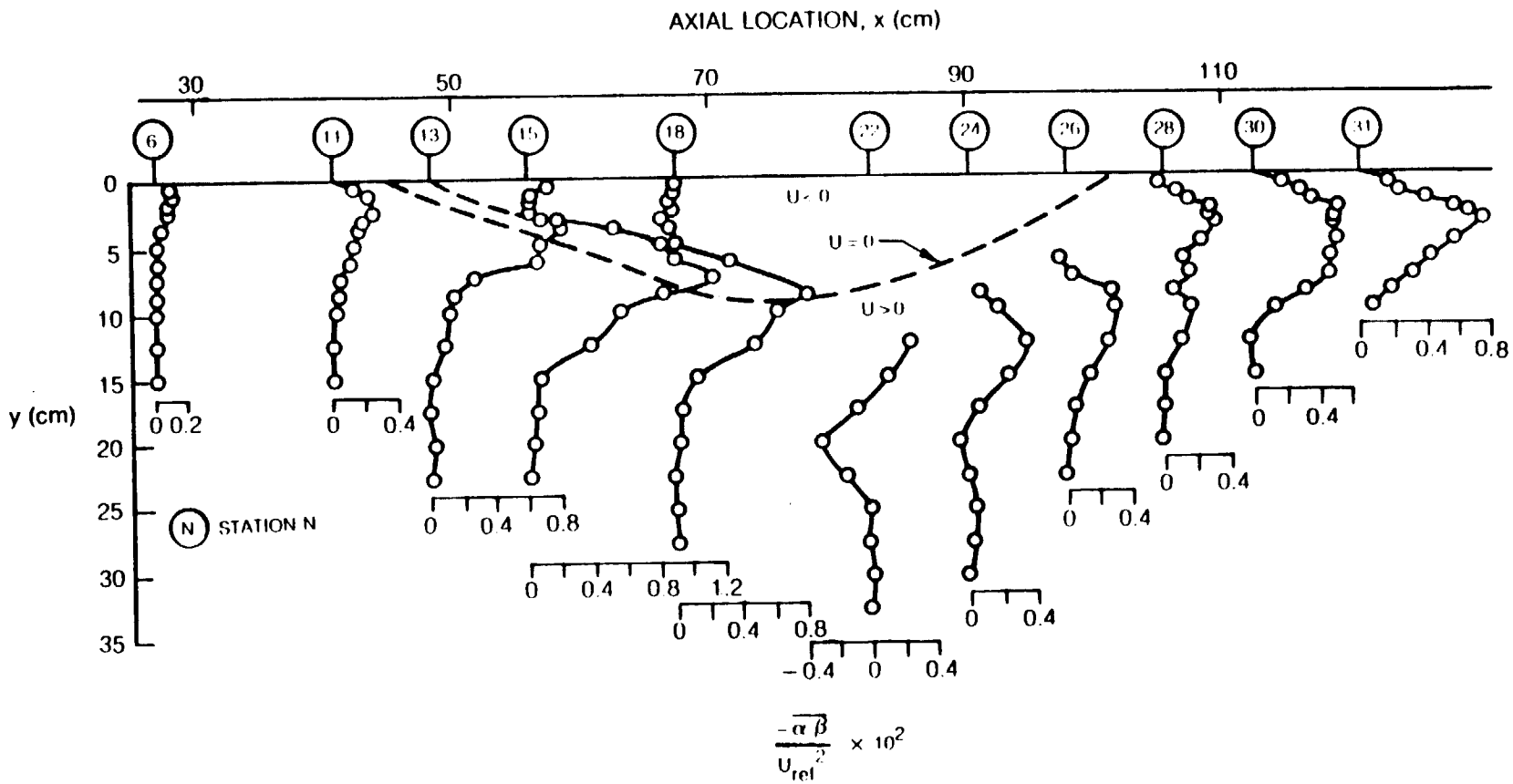


83-7-16-1

NONDIMENSIONAL REYNOLDS STRESS PROFILES DETERMINED WITH LASER VELOCIMETER (z = 0)

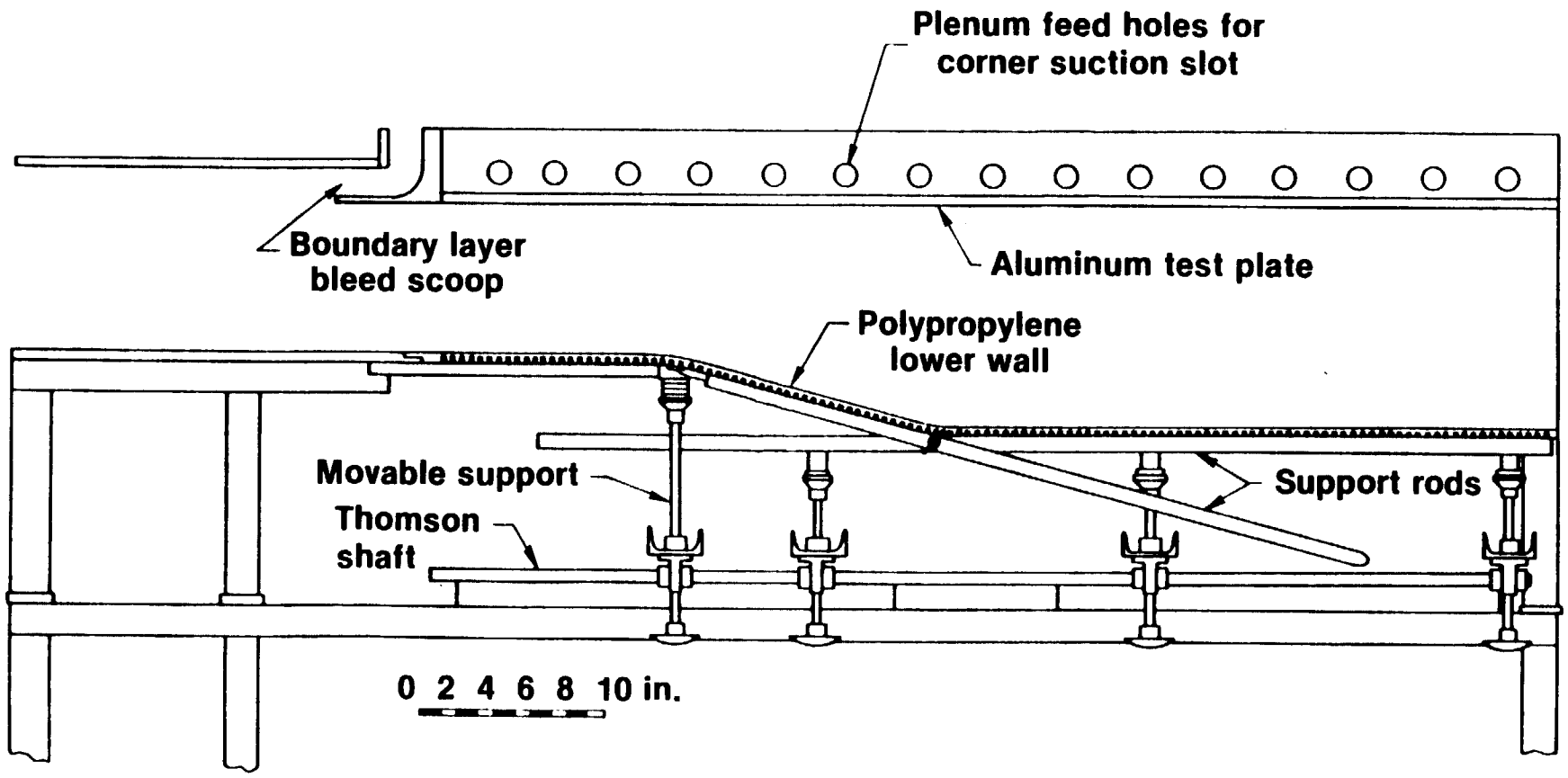


NONDIMENSIONAL STREAMWISE SHEAR STRESS PROFILES DETERMINED FROM LASER VELOCIMETER DATA (z = 0)



87-7-10-5

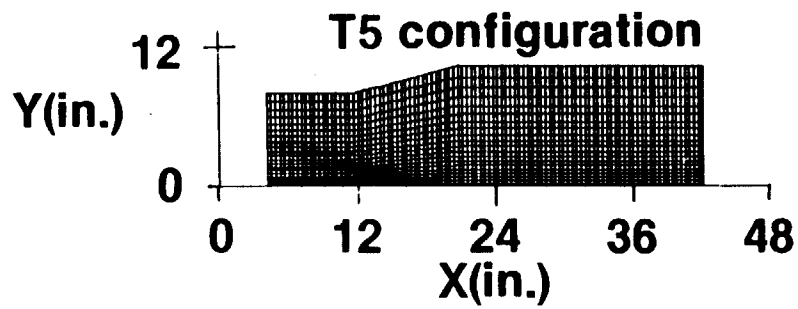
TEST SECTION FOR LAMINAR SEPARATION BUBBLE STUDIES

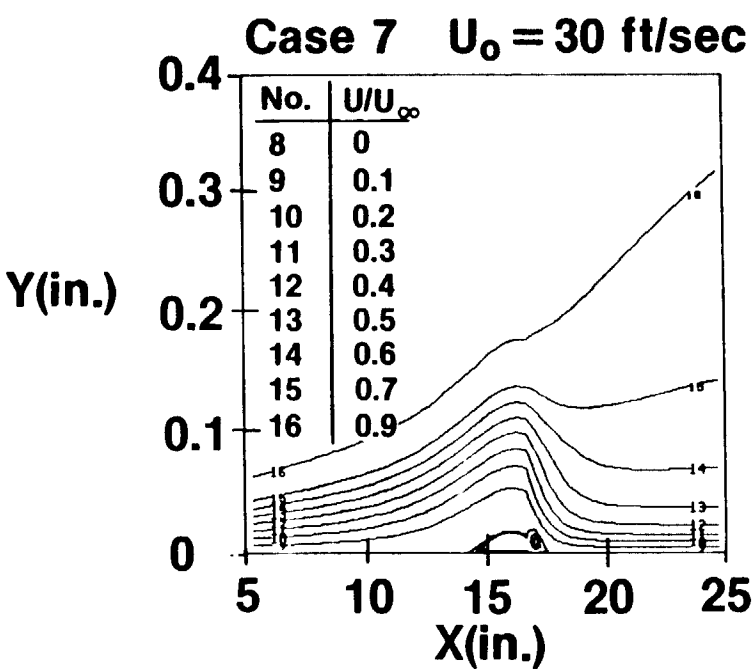


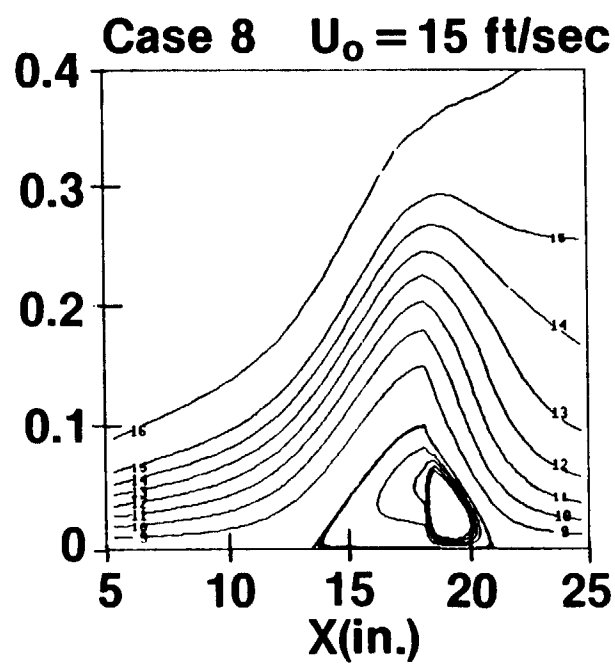
85-6-45-6

EFFECT OF FLOW SPEED ON SIZE OF LAMINAR SEPARATION BUBBLE

($X_o = 12$ in., $\alpha = 15$ deg)







85-6-45-4

EXPERIMENTAL/ANALYTICAL RESEARCH PROGRAM FOR LOW REYNOLDS NUMBER SEPARATION BUBBLES

Phase I: Exploratory studies

- Definition of flow conditions
- Analytical screening
- Experimental screening
- Experimental definition of baseline case

Phase II: Detailed studies of baseline case

- Measurements
- Data analysis
- Code assessment

Phase III: Sensitivity studies

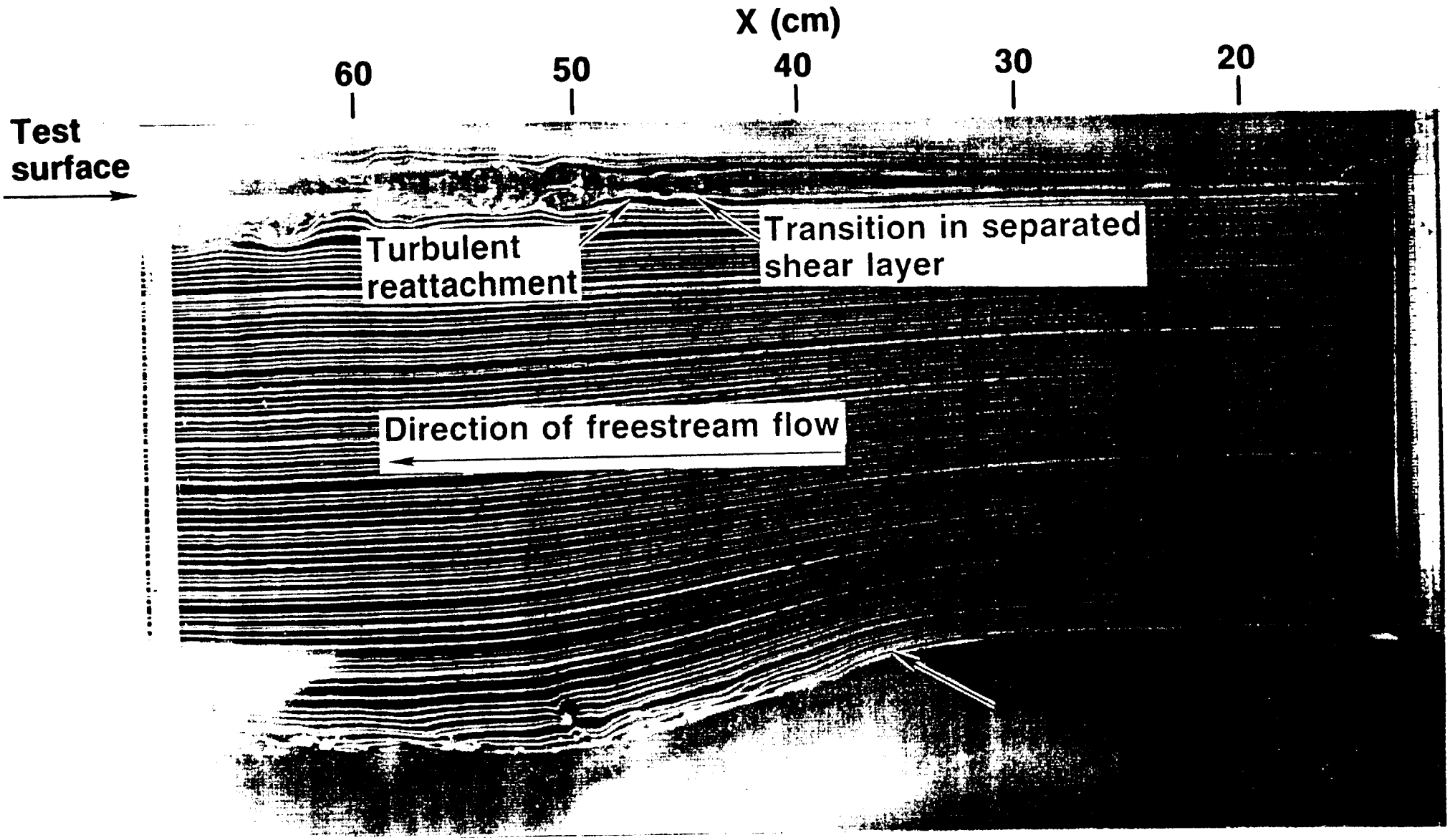
- Reynolds number variations
- Pressure gradient variations
- Turbulence intensity variations
- Turbulence scale variations
- Code assessments
- Other effects

Phase IV: Additional sensitivity studies

- Surface curvature
- Surface roughness
- Code assessment

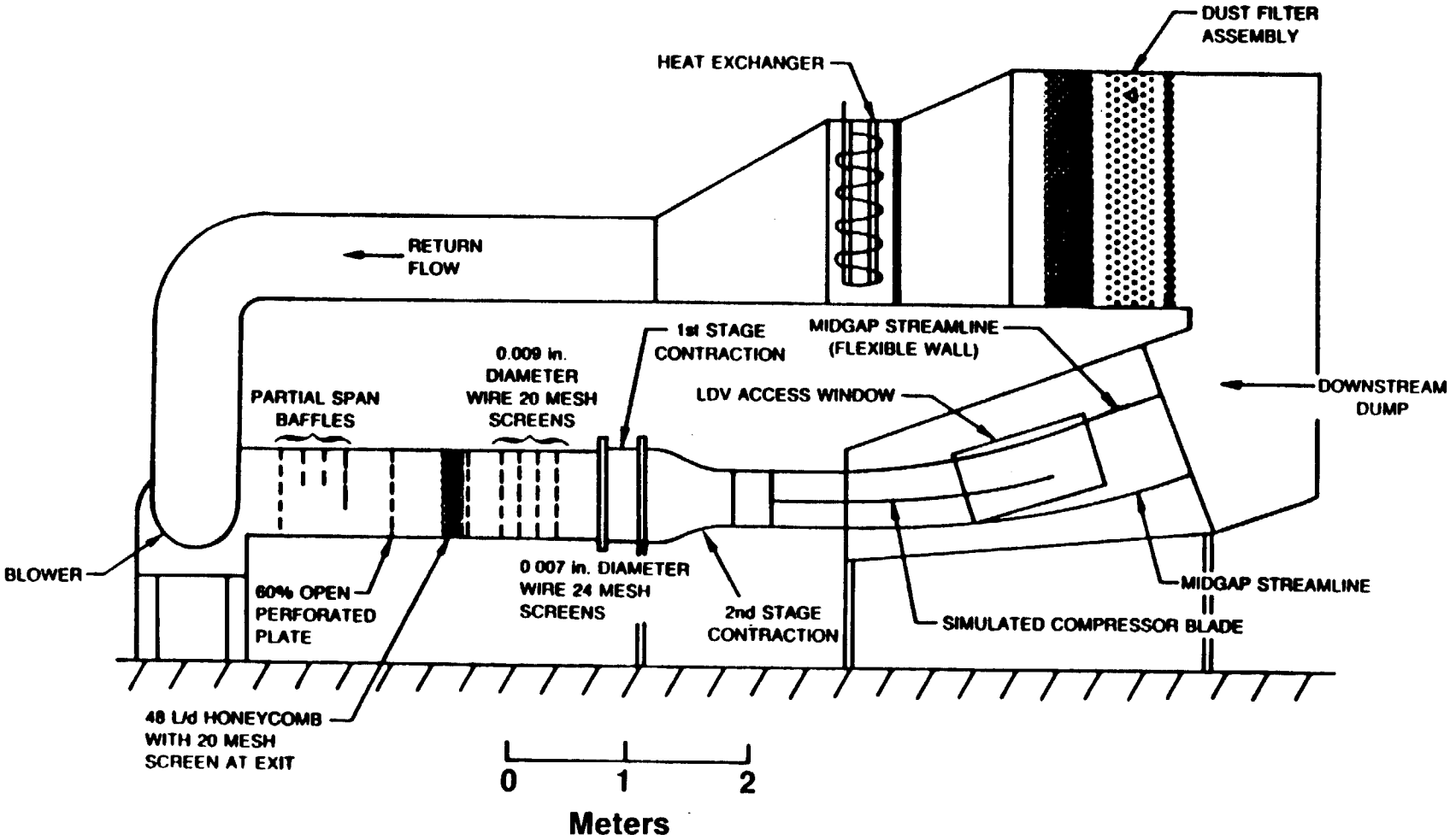
RD660TX.002

LAMINAR SEPARATION BUBBLE WITH TURBULENT REATTACHMENT



87-7-10-1

LARGE SCALE CASCADE SIMULATION

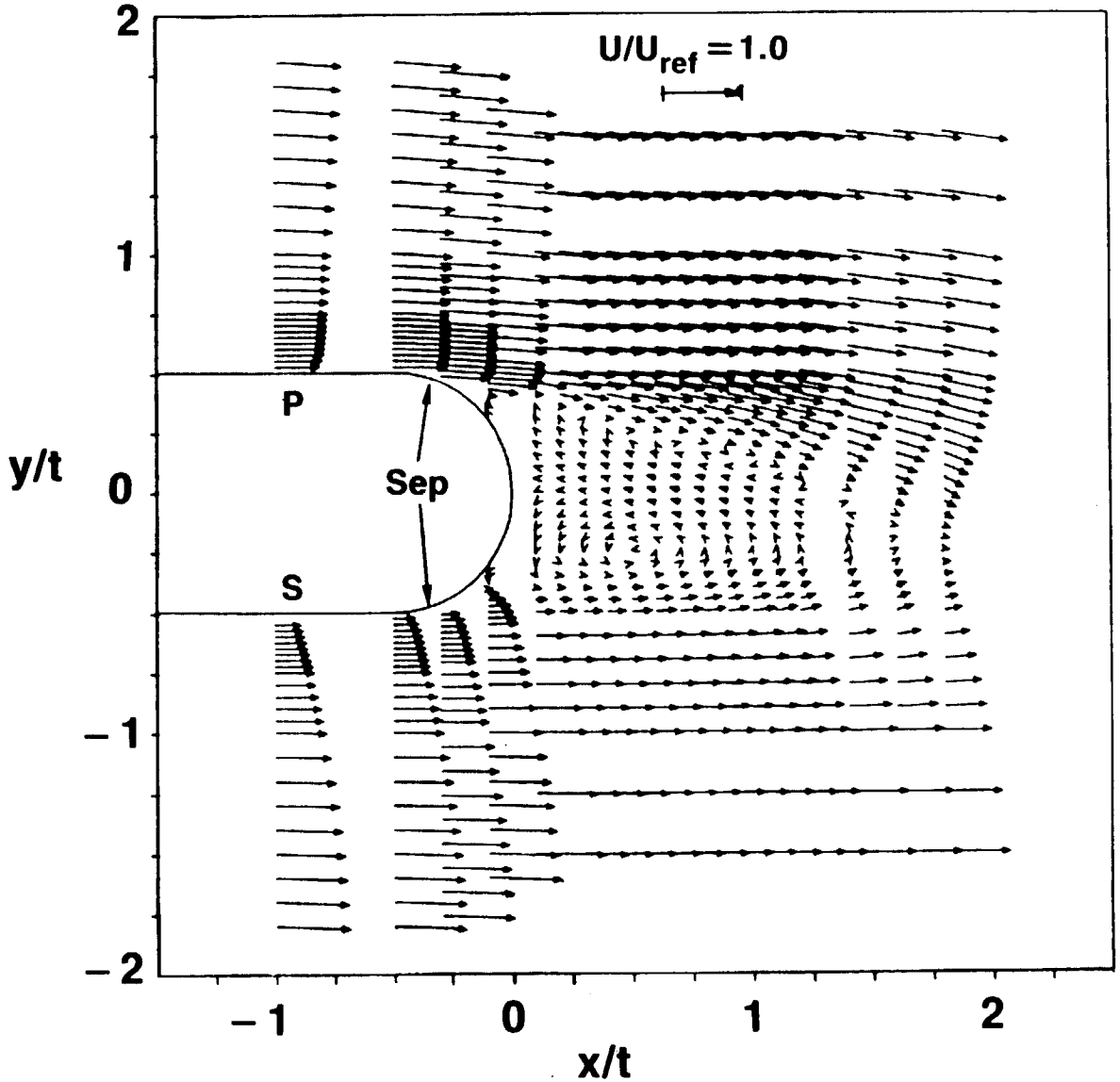


87-7-10-3

COMPRESSOR TRAILING EDGE SEPARATION

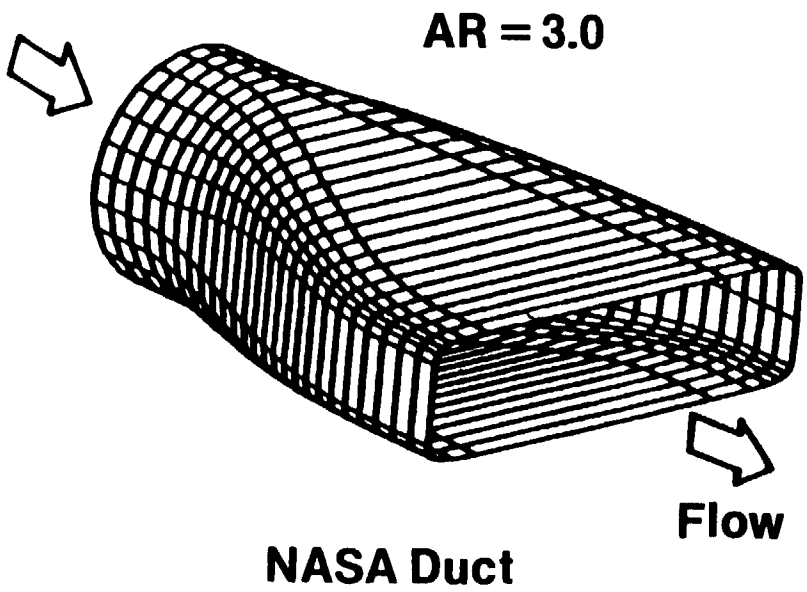
LV velocity measurements in near wake

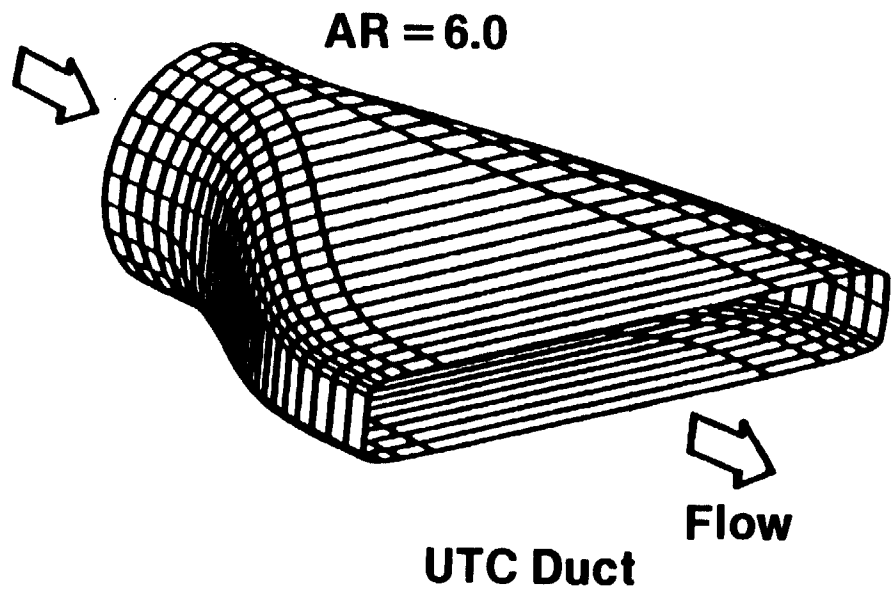
Low loading case



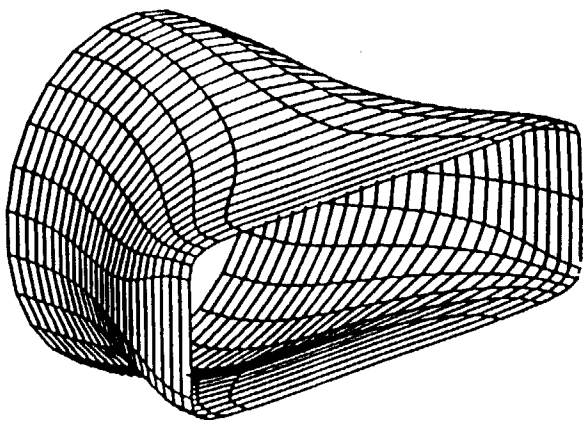
87-7-10-2

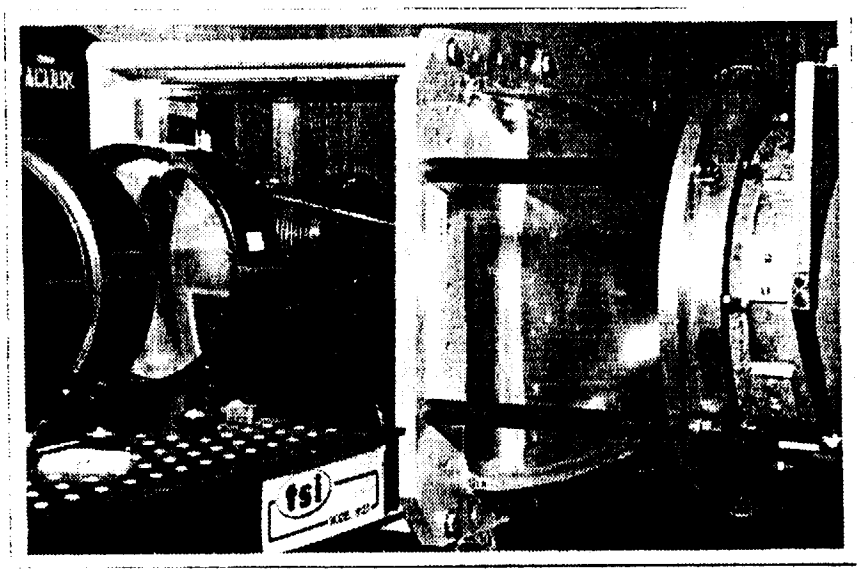
TRANSITION DUCT PROGRAM



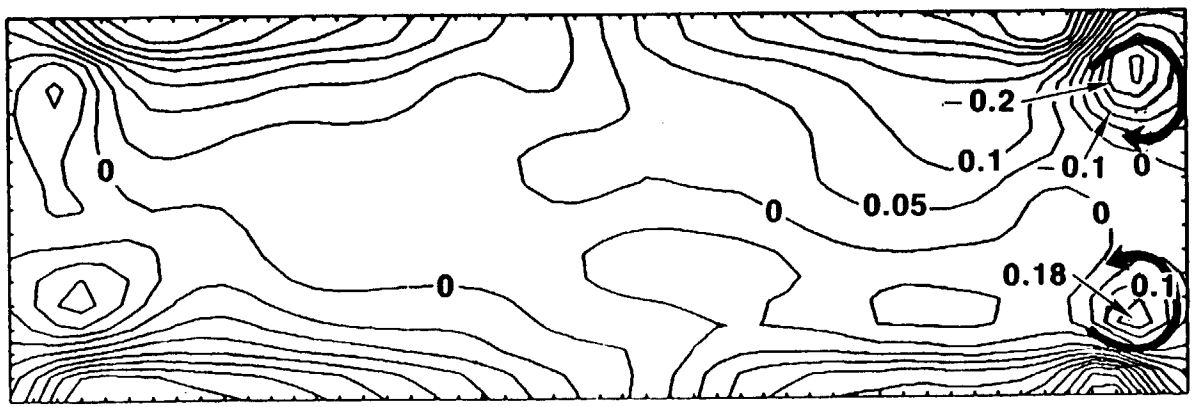


TRANSITION DUCT FLOWS



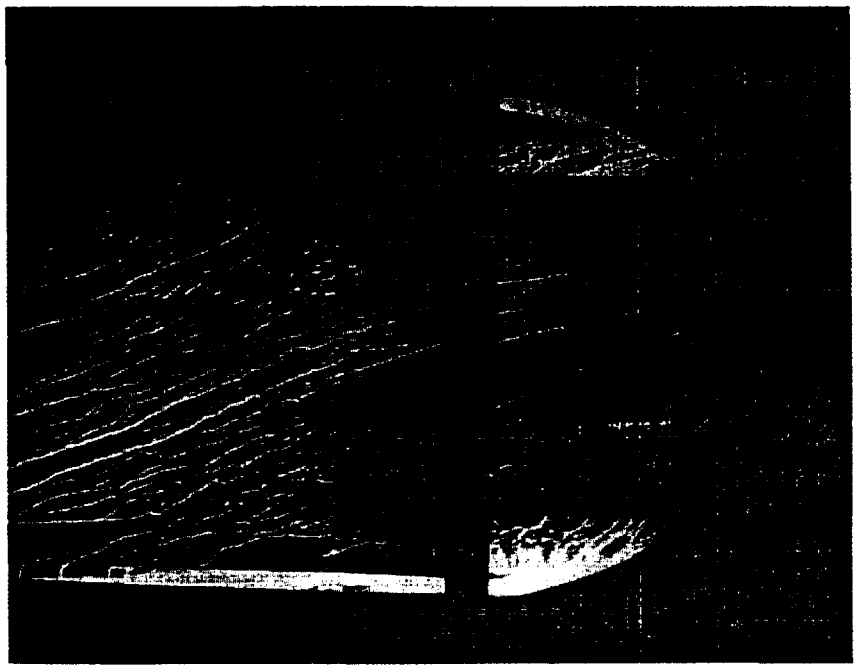


Axial vorticity contours

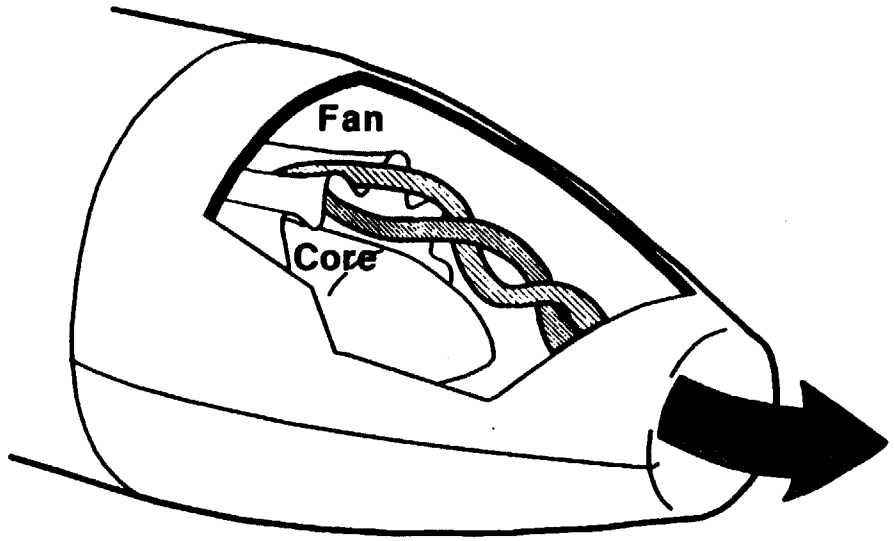


87 – 20 #5

87 – 6 – 25 – 10



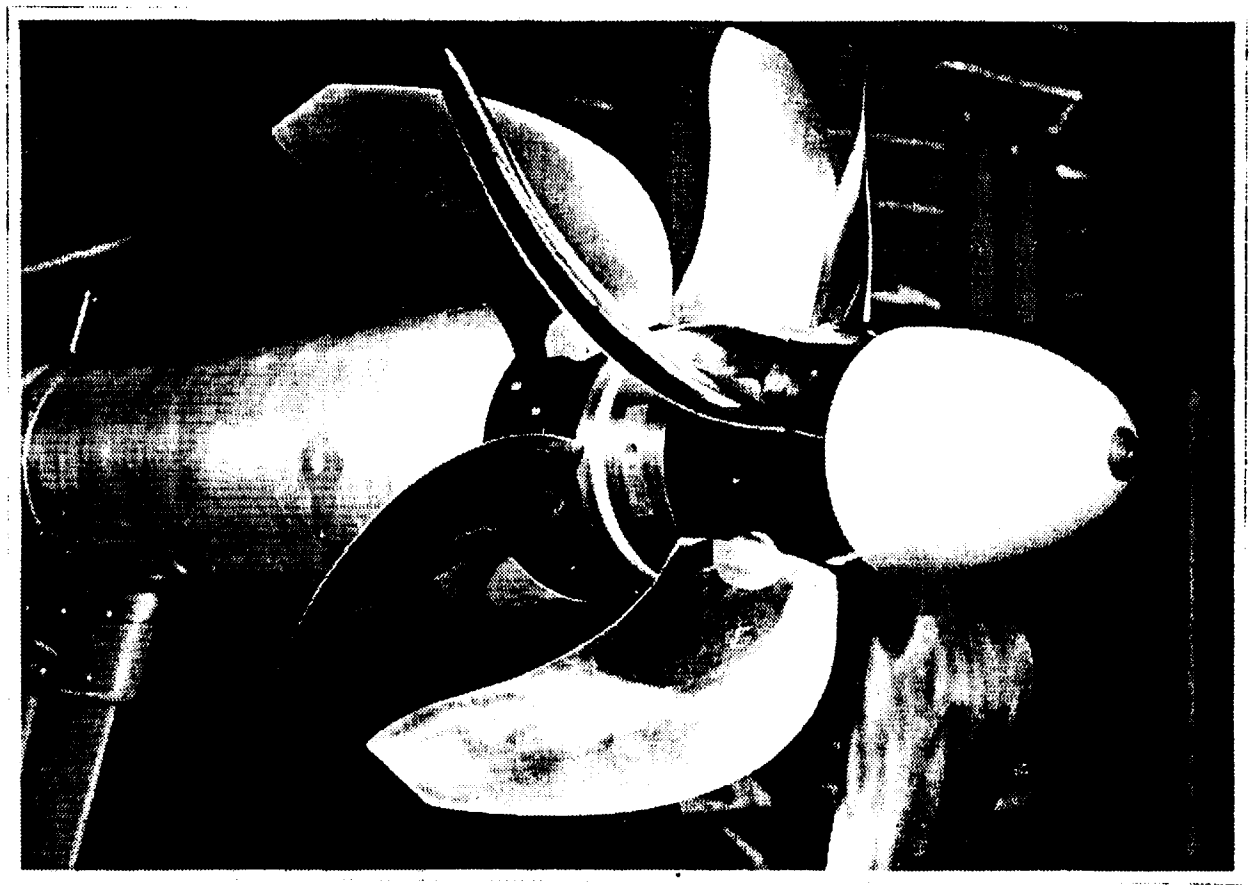
FORCED MIXER STUDIES



- Subsonic mixers
- Mixer ejectors
- Rippled trailing edge
- Supersonic mixer nozzles

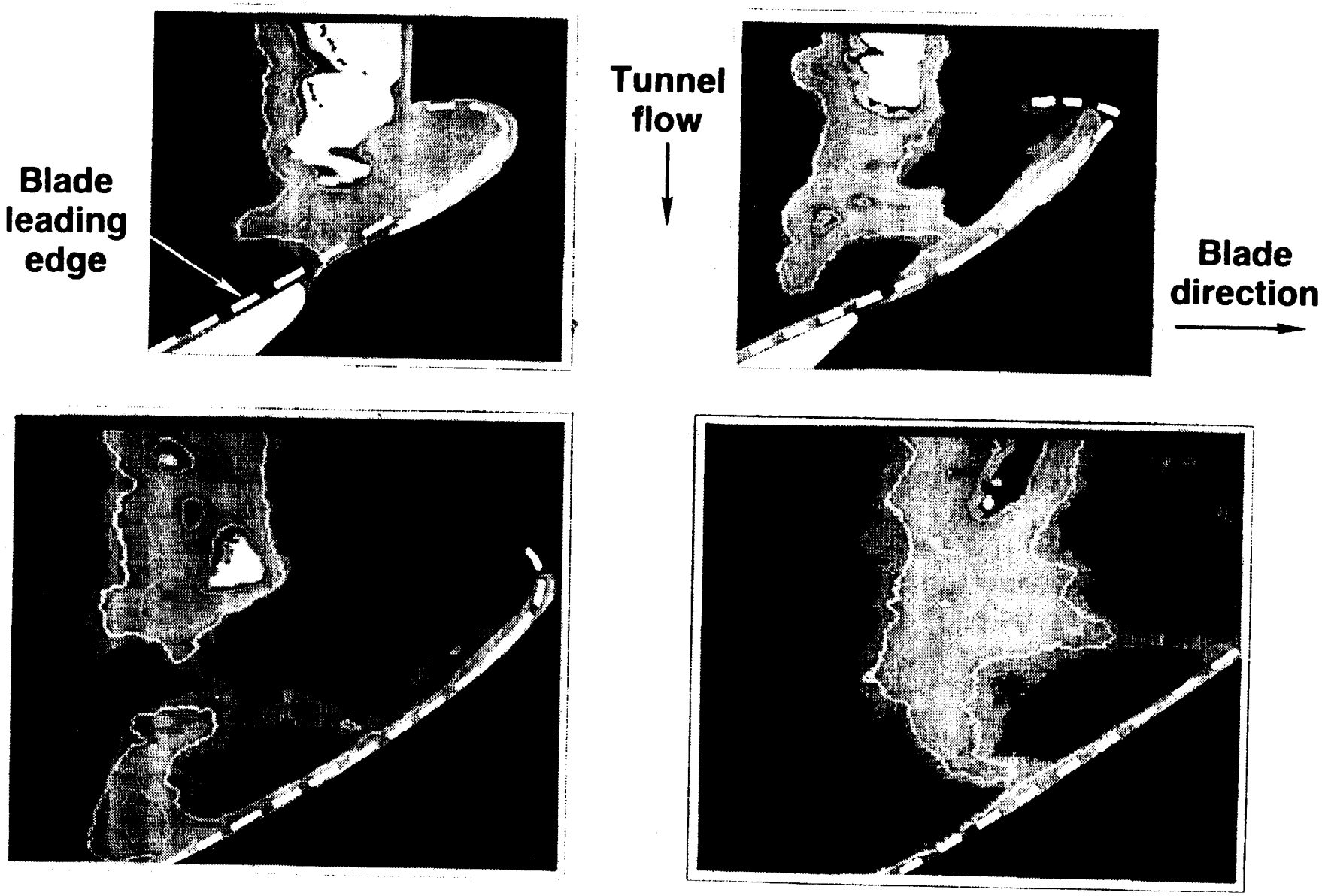
RA2249TX.009

CRP-XI COUNTER ROTATION PROP-FAN MODEL



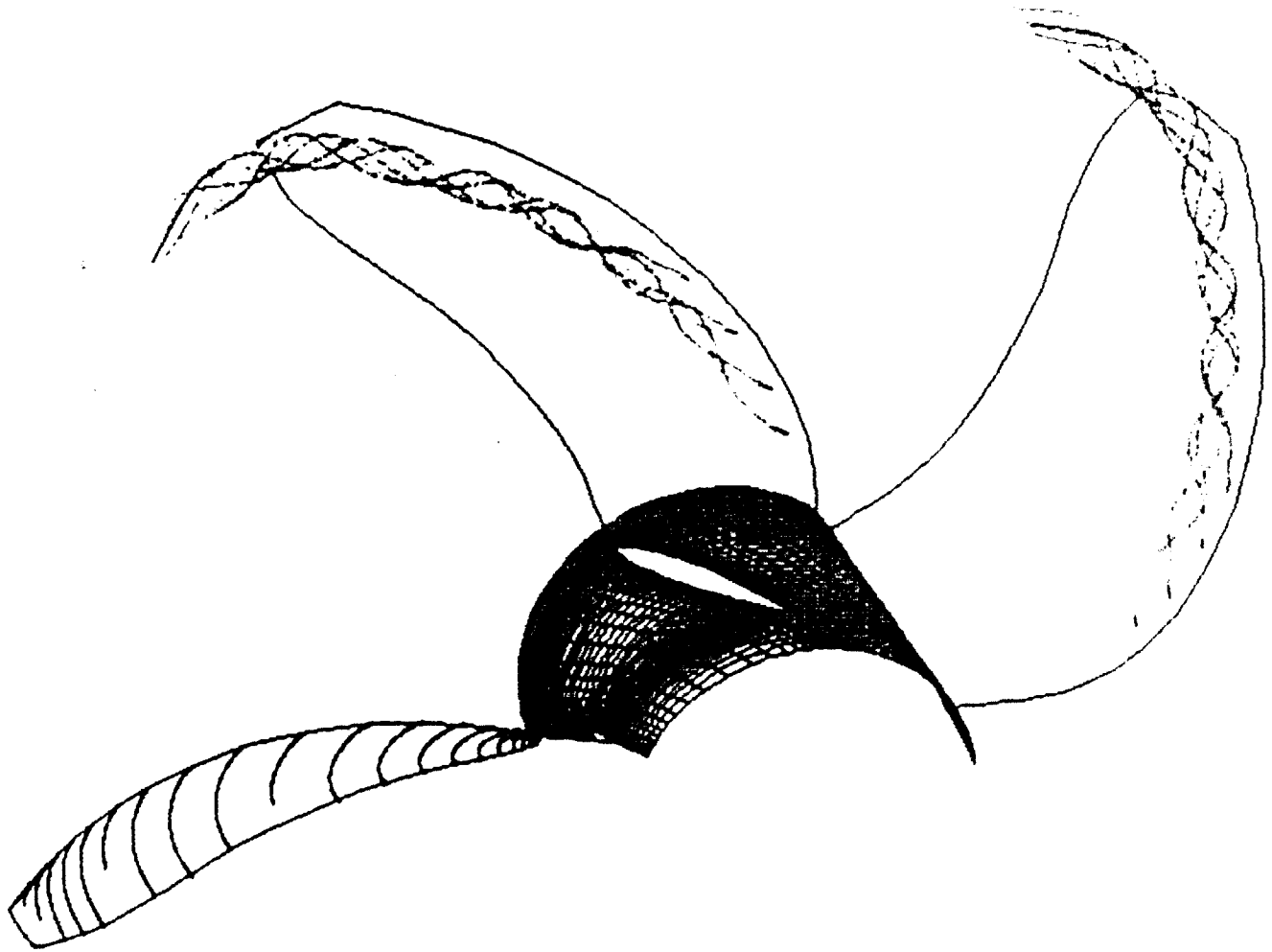
86-84-F10

86-9-12-4



86—9—1—3

HAMILTON STANDARD CRP-X1 PROP-FAN



$M_\infty = 0.2$

ADVR = 1.0

641

UNITED TECHNOLOGIES RESEARCH CENTER

Streamlines

87 6-67-4

BENCHMARK EXPERIMENTATION - CRITICAL FACTORS

Test geometry	Operating conditions	Measured variables	Spatial resolution	Instrumen-tation	Error estimates

RA2249TX.007

BENCHMARK EXPERIMENTATION - CRITICAL FACTORS

Test geometry	Operating conditions	Measured variables	Spatial resolution	Instrumen-tation	Error estimates

- Simplest relevant geometry

RA2249TX.006

BENCHMARK EXPERIMENTATION - CRITICAL FACTORS

Test geometry	**Operating conditions**	Measured variables	Spatial resolution	Instrumen-tation	Error estimates

- Non-dimensional ratios such as Mach number, Reynolds number, temperature ratio, velocity ratios, and length scale ratios must be examined to determine which are of first and second order of importance
- Single condition experiments are dangerous

RA2249TX.002

BENCHMARK EXPERIMENTATION - CRITICAL FACTORS

Test geometry	Operating conditions	**Measured variables**	Spatial resolution	Instrumen-tation	Error estimates

- Must measure variables required for code input
- Must measure variables predicted by code
- Must consult with CFD group

RA2249TX.003

BENCHMARK EXPERIMENTATION - CRITICAL FACTORS

Test geometry	Operating conditions	Measured variables	Spatial resolution	Instrumen-tation	Error estimates

- High spatial resolution almost always critical
- Large scale simulation may be required

RA2249TX.005

BENCHMARK EXPERIMENTATION - CRITICAL FACTORS

Test geometry	Operating conditions	Measured variables	Spatial resolution	Instrumen-tation	Error estimates

- Usually requires a mix of flow diagnostics
- Non-intrusive techniques such as LV required to prevent disruption of flowfield

RA2249TX.004

BENCHMARK EXPERIMENTATION - CRITICAL FACTORS

Test geometry	Operating conditions	Measured variables	Spatial resolution	Instrumen-tation	Error estimates

- Experimentalists should be schooled in uncertainty analysis
- Uncertainty estimates on all measured variables should be performed prior to experiment. This is particularly important for LV measurements
- Error bars should be specified for reported data

RA2249TX.001

VERIFICATION OF 3D VISCOUS/TURBULENT CODES FOR INTERNAL FLOWS

N92-70949

B. LAKSHMINARAYANA
DEPARTMENT OF AEROSPACE ENGINEERING
THE PENNSYLVANIA STATE UNIVERSITY

1. SPACE MARCHING TECHNIQUE
   - A. COMPRESSIBLE FLOW
   - B. INCOMPRESSIBLE FLOW
   - C. VALIDATION FOR INTERNAL FLOW
     - CASCADES BLADE BL/ENDWALL FLOWS
     - DUCTS
     - WING (3D)
     - 90° BEND
     - ROTATING CHANNEL

2. NEW PARABOLIC MARCHING TECHNIQUE
   - METHOD
   - VALIDATION CASCADE WAKES, IGV PASSAGE FLOW

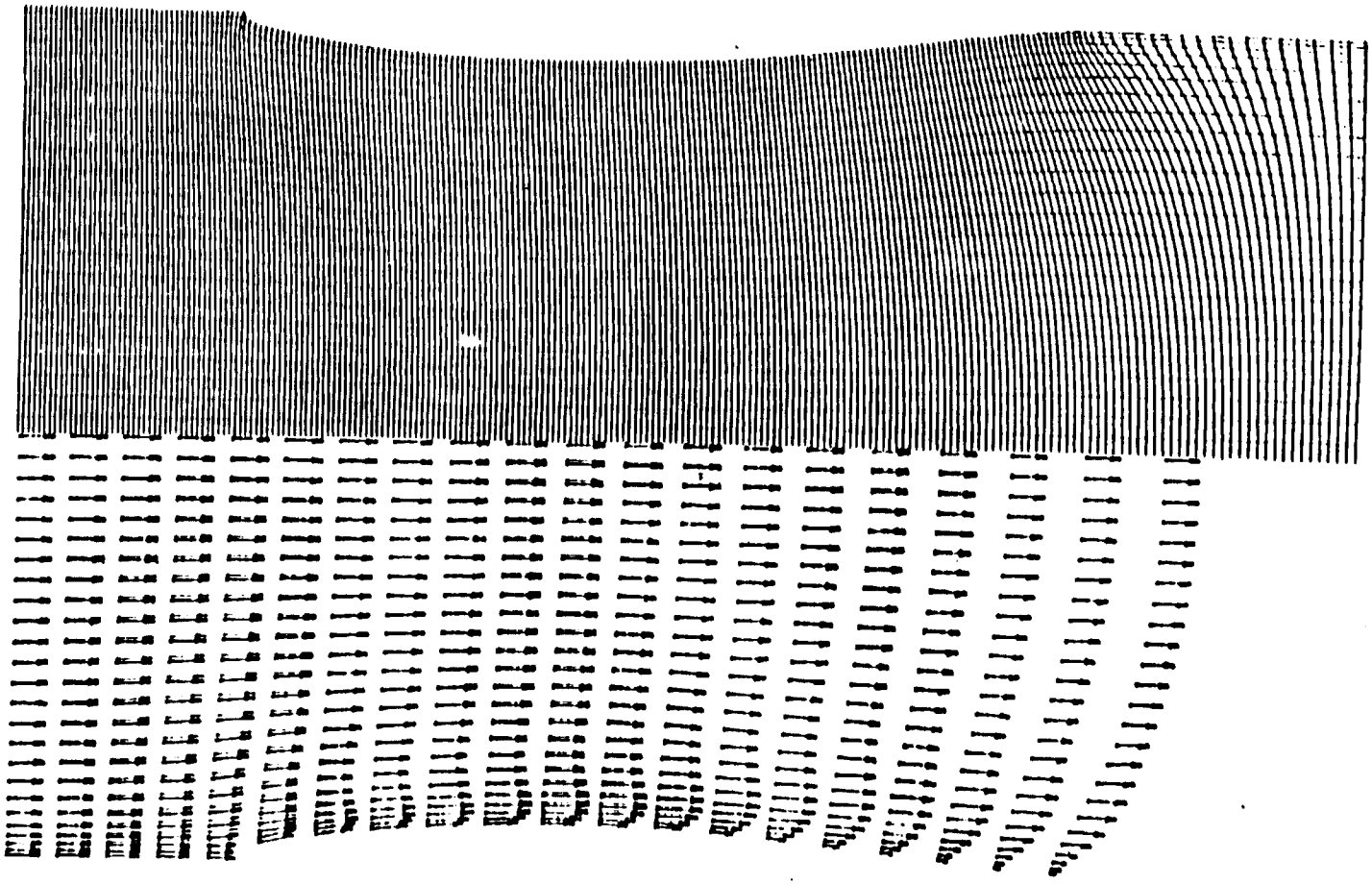
3. PSEUDOCOMPRESSIBILITY CODE
   - METHOD DUE TO KWAK/MODIFICATIONS
   - VALIDATION OF PSU ROTOR DATA

4. COMPARISON OF TIME MARCHING/SPACE MARCHING CODES
   - COMPARISON FOR CASCADE ENDWALL FLOW

5. ZONAL TECHNIQUE
   - 2D AND 3D
   - PRELIMINARY RESULTS

6. CONCLUSIONS

NACA 65-010 c/s = 1.0



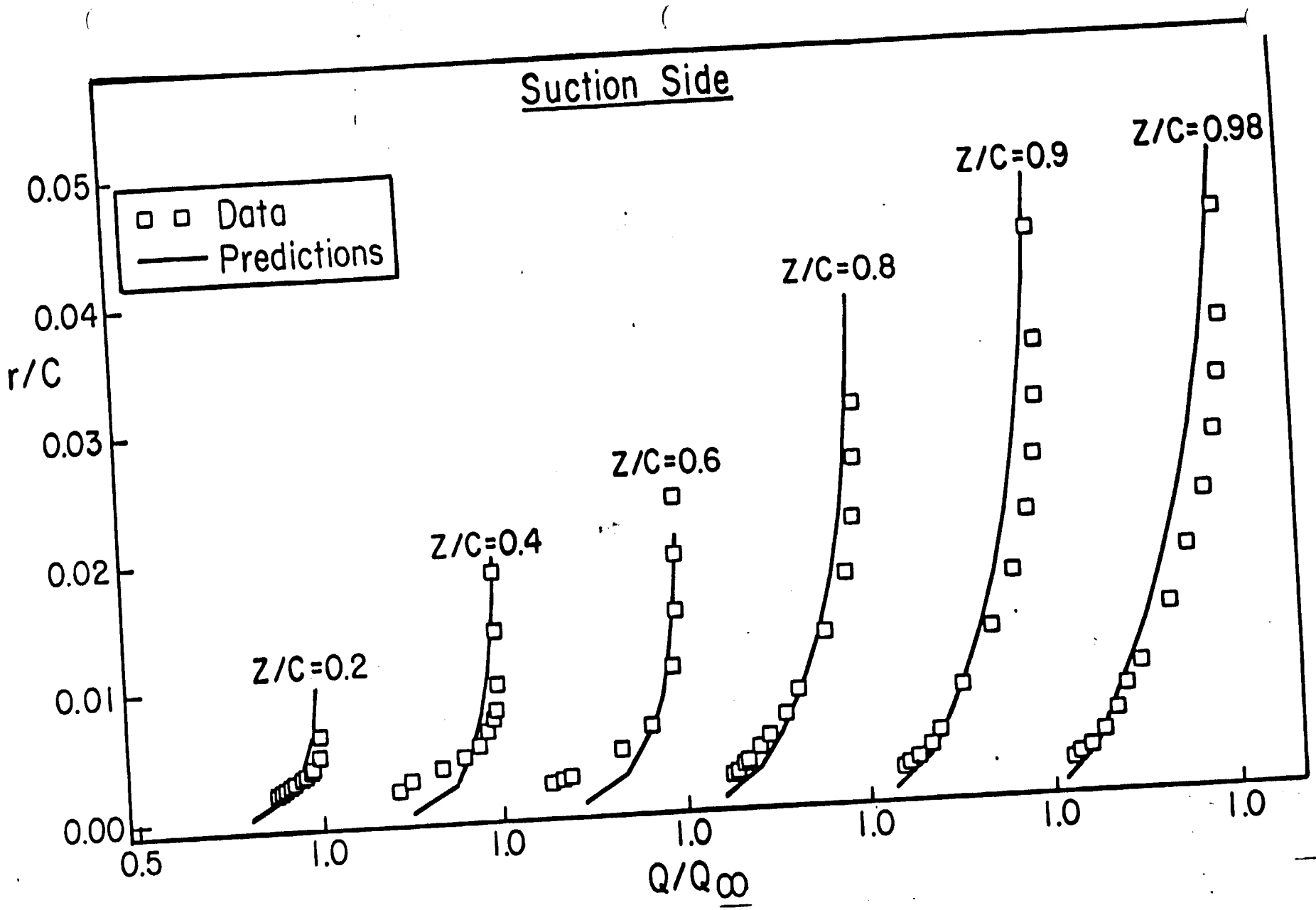
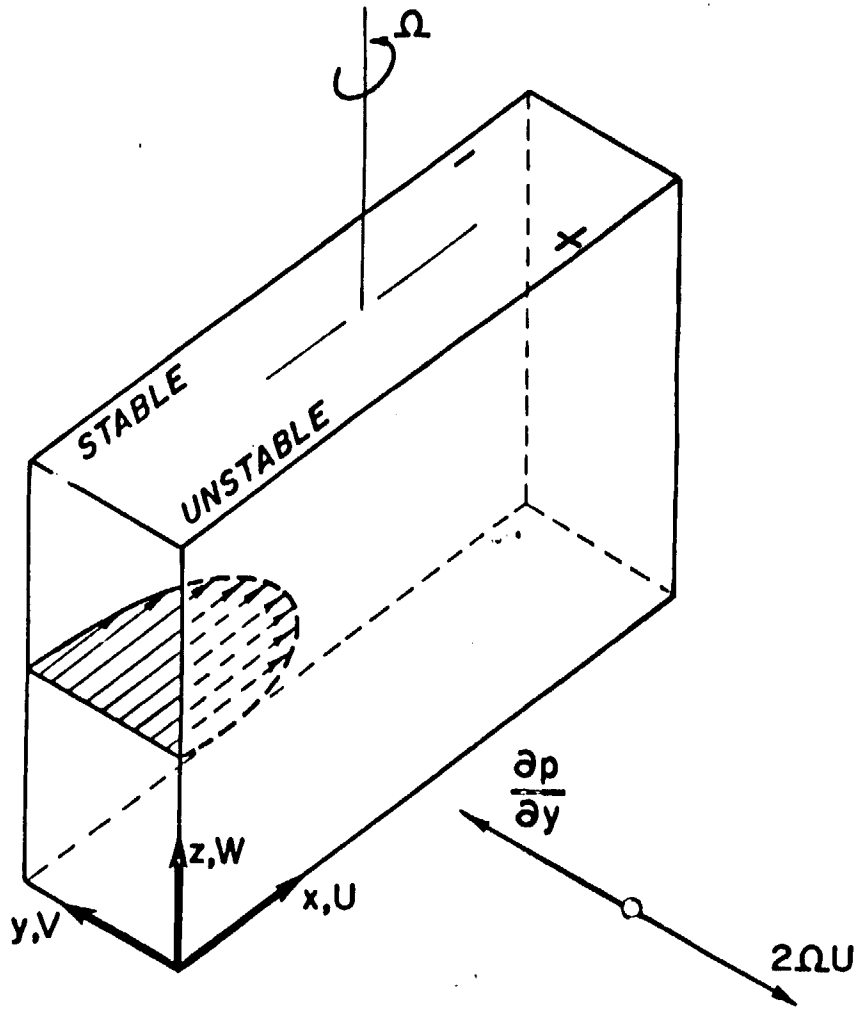


Fig. 10. Boundary Layer Profiles on the Suction Side of Peterson's Cascade



THE MODEL REPRESENTATIVE OF CENTRIFUGAL TYPE OF TURBOMACHINERY

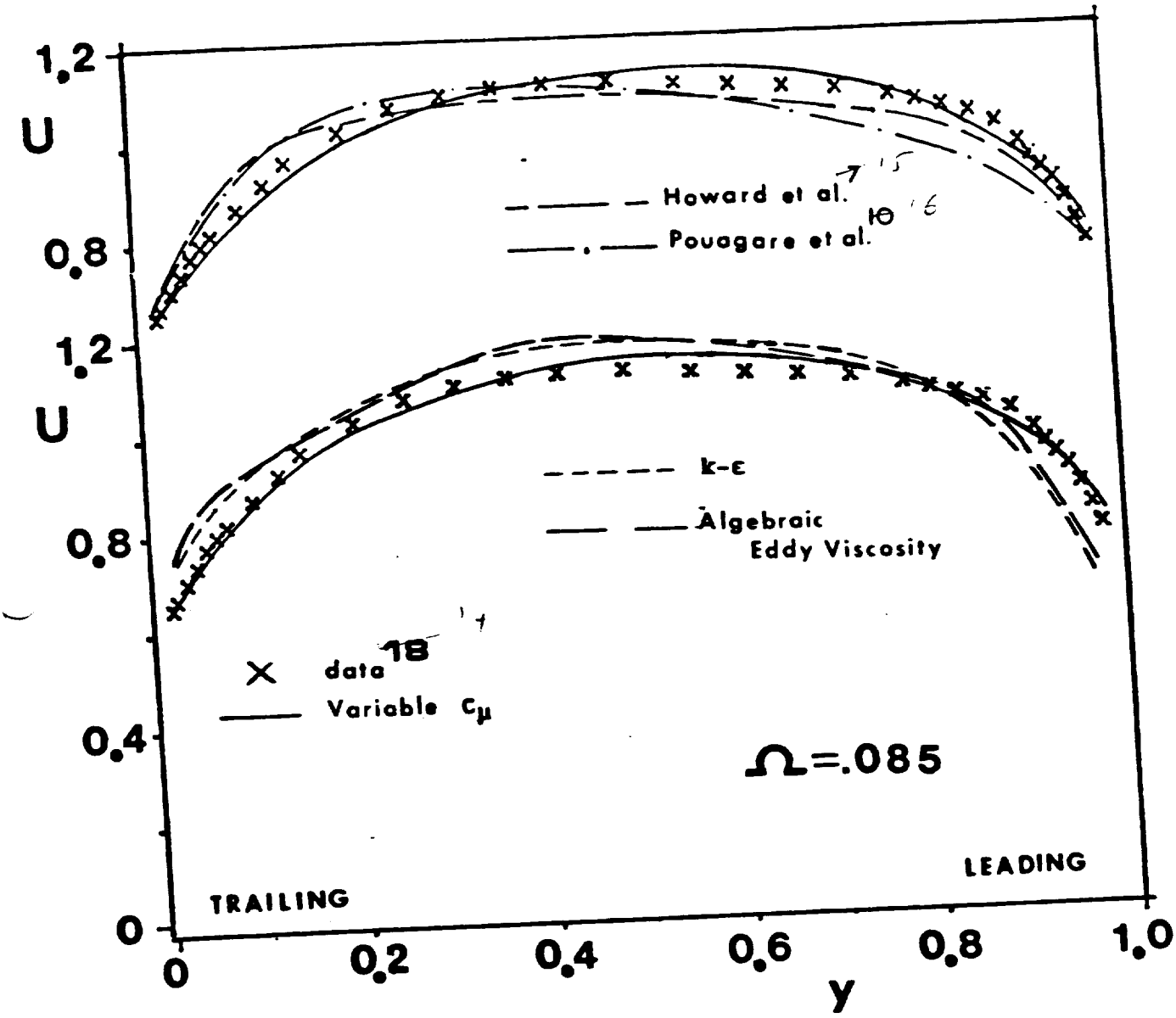


Figure 7 Comparison of Velocity Profiles with Modified and Unmodified Turbulence Models for a Flow in a Rotating Channel; Re=35,000

Fig 4

p)Comparison Between Modified Models

4) ACHIEVE DIVERGENCE FREE VELOCITY FIELD AT CONVERGENCE

3) INITIAL SWEEPS OF COMPLEX FLOWS ARE MORE SUCCESSFUL

2) SYSTEM CONVERGES FASTER WHEN $\rho \neq 0$ FOR COMPLEX FLOWS

1) DIAGONAL DOMINANCE ASSURED

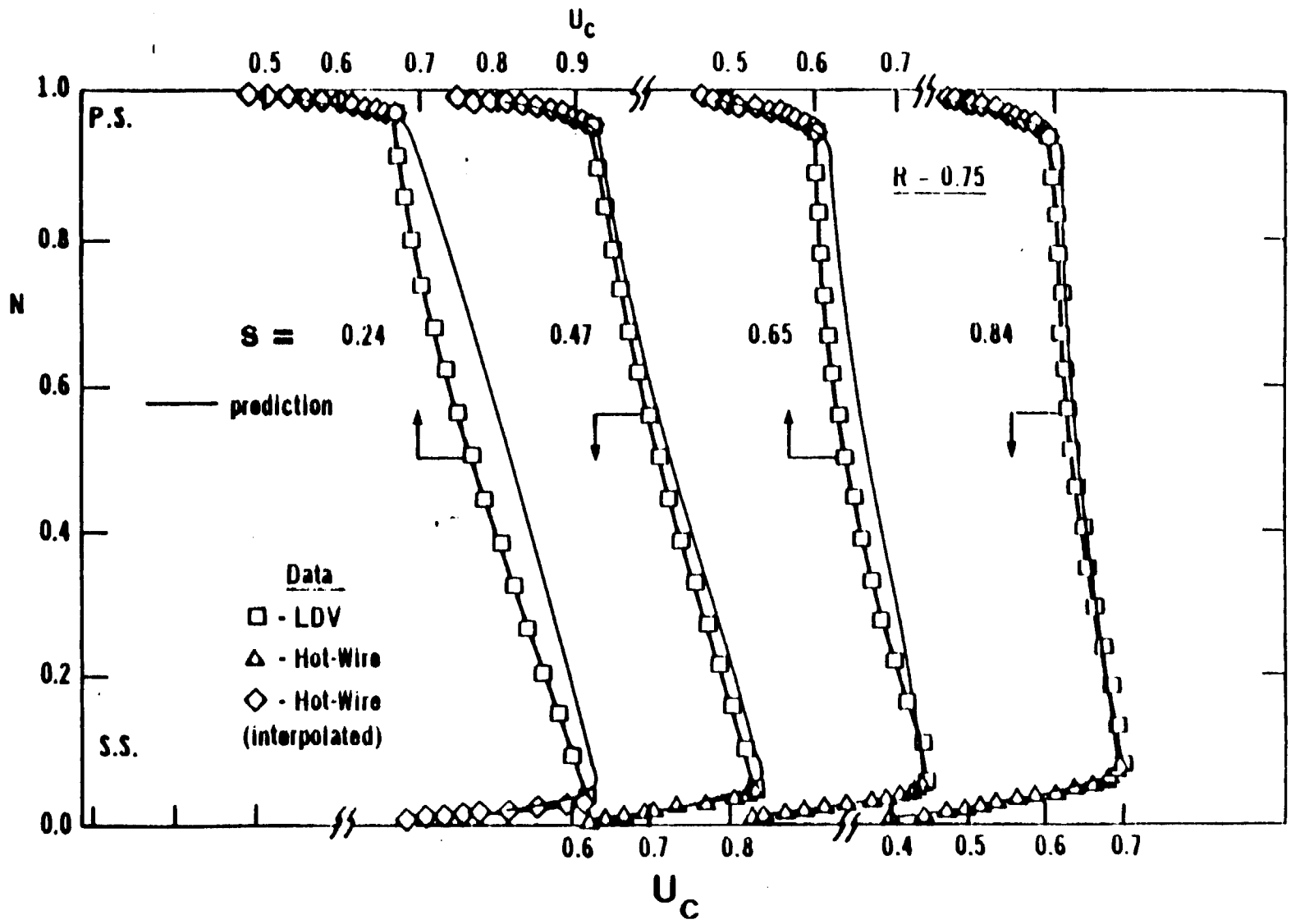
ATTRIBUTES:

$$A = \begin{bmatrix} wu \\ uv \\ u\lambda^2 + b \\ u + \rho_b \end{bmatrix} \qquad B = \begin{bmatrix} wv \\ v\lambda^2 + b \\ uv \\ v \end{bmatrix} \qquad C = \begin{bmatrix} w\lambda^2 + b \\ wv \\ uw \\ w \end{bmatrix} \qquad D = \begin{bmatrix} w \\ v \\ u \\ 0 \end{bmatrix} \qquad Z = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \rho_b u_{-1} \end{bmatrix}$$

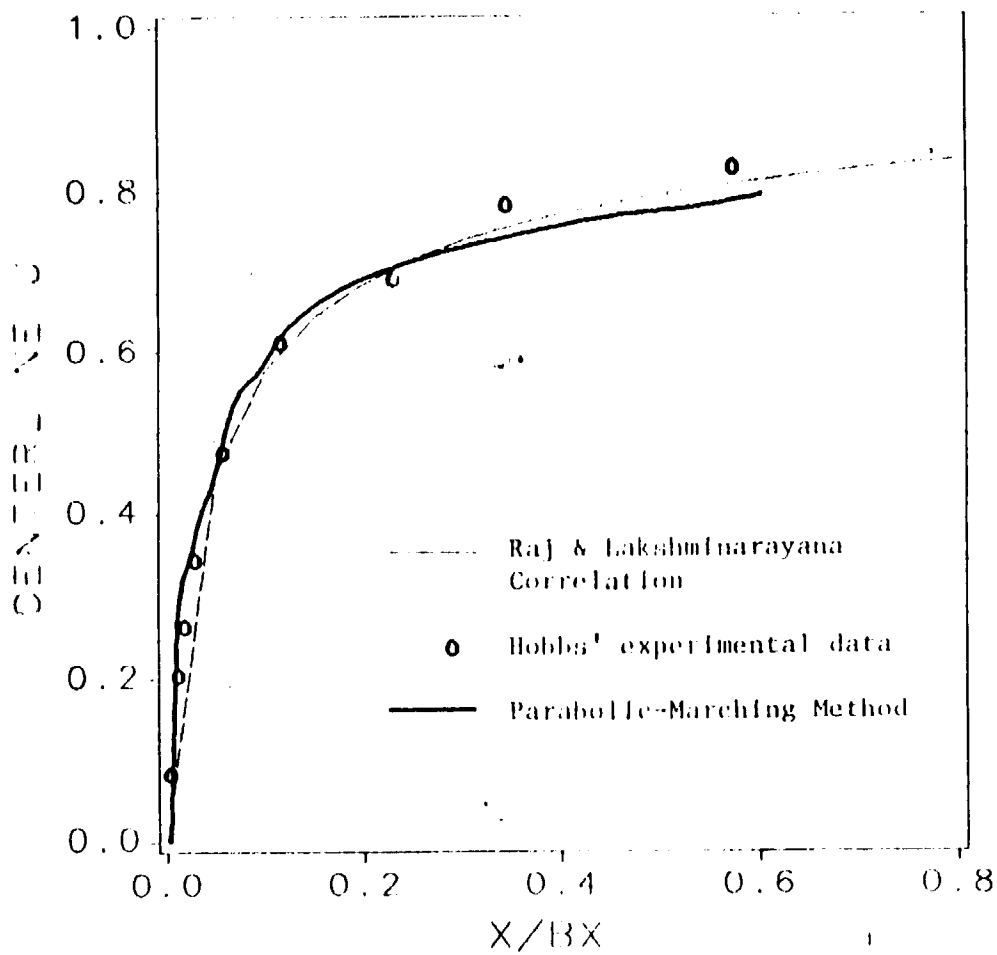
$$\frac{\partial x}{\partial V} + \frac{\partial y}{\partial B} + \frac{\partial z}{\partial C} - \frac{\partial t}{\partial J} = \begin{bmatrix} \frac{\partial z}{\partial D} + \frac{\partial y}{\partial D} \end{bmatrix} = Z$$

THUS, THE FOLLOWING COUPLED FORM OF THE EQUATION IS SOLVED

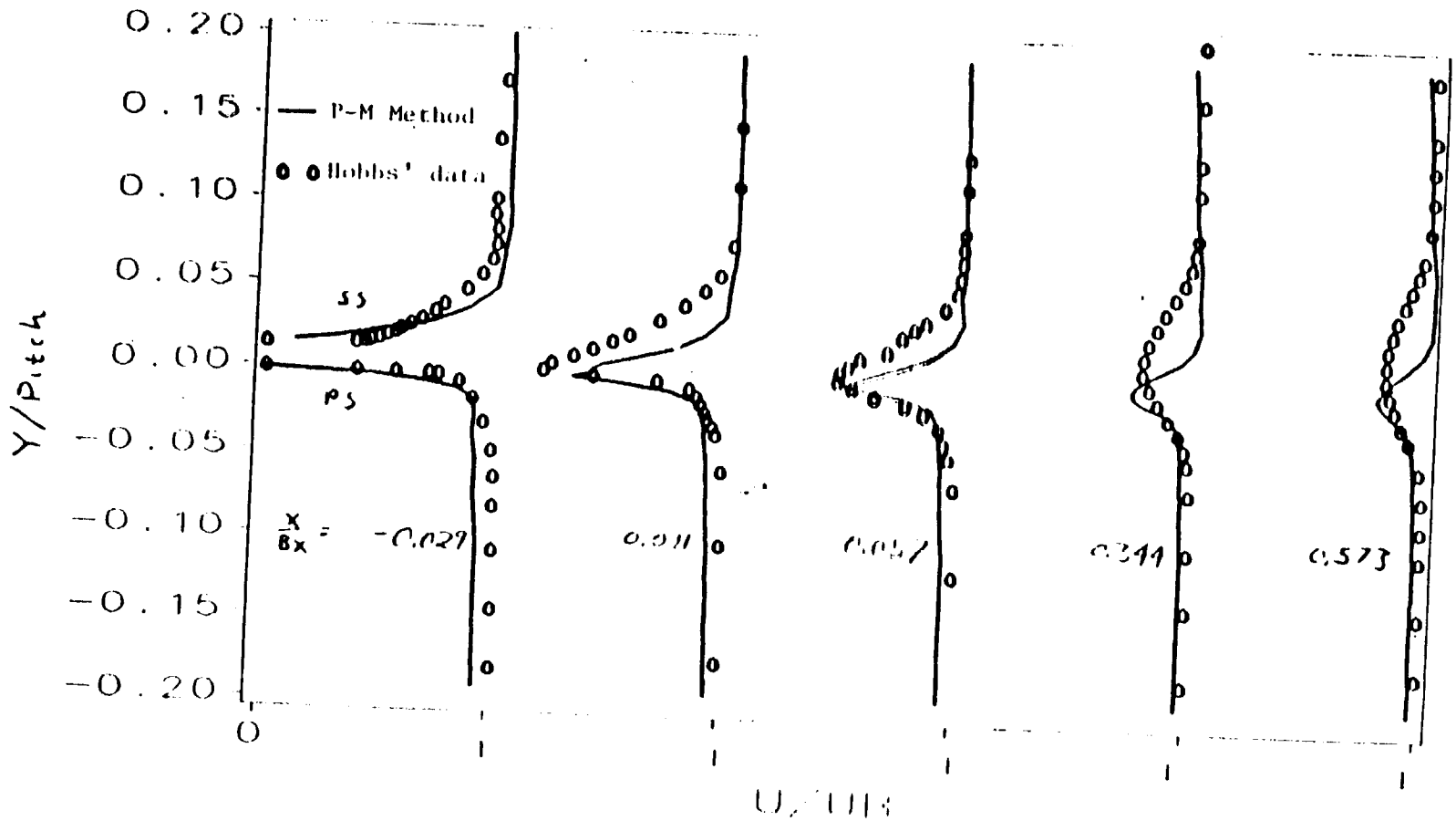
COMPOSITE VELOCITY PREDICTION AT R=0.75 FOR ϕ=0.50

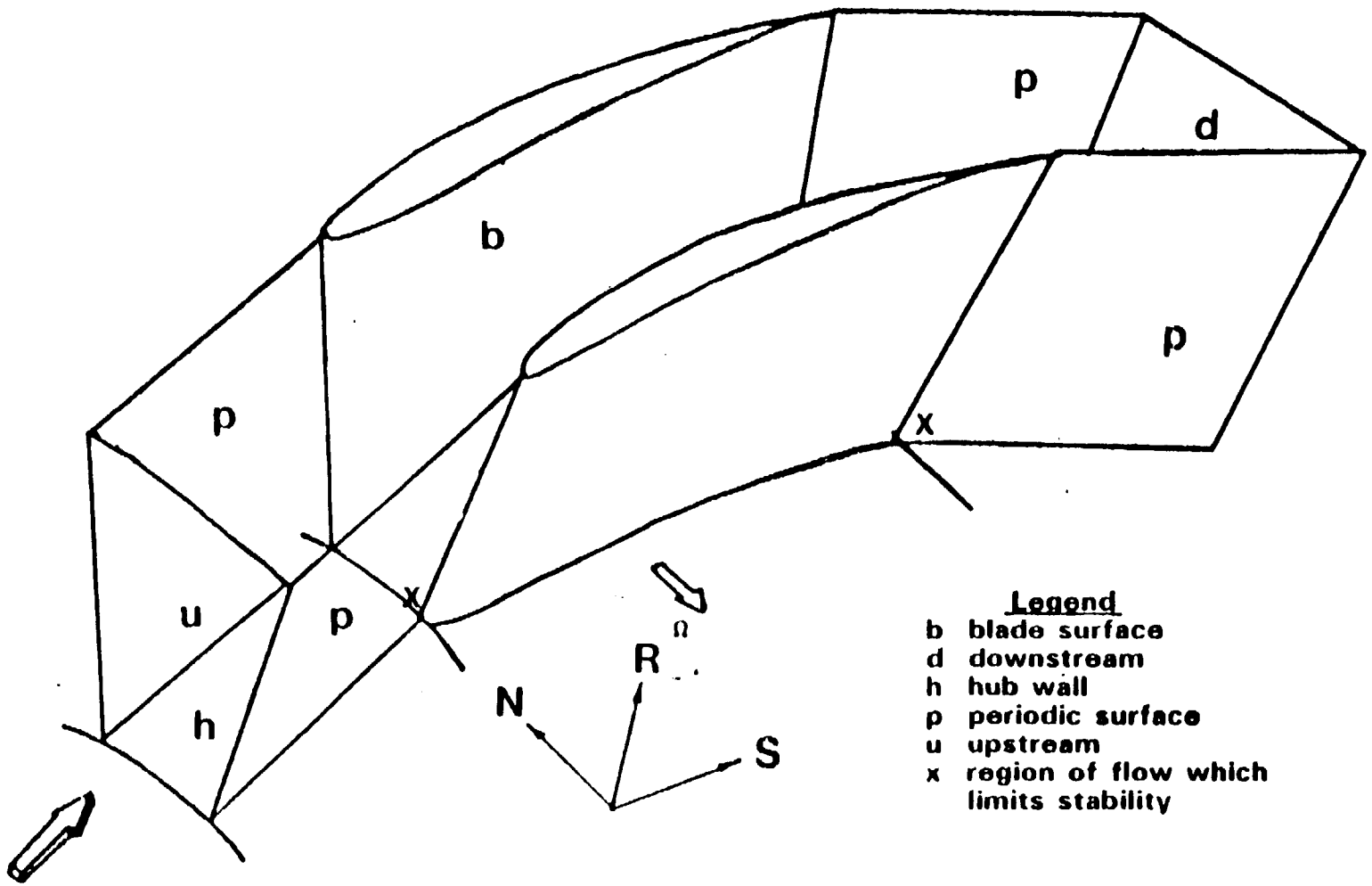


WAKE CENTERLINE VELOCITY FOR HOBBS CASCADE



STREAMWISE WAKE PROFILES HOBBS II



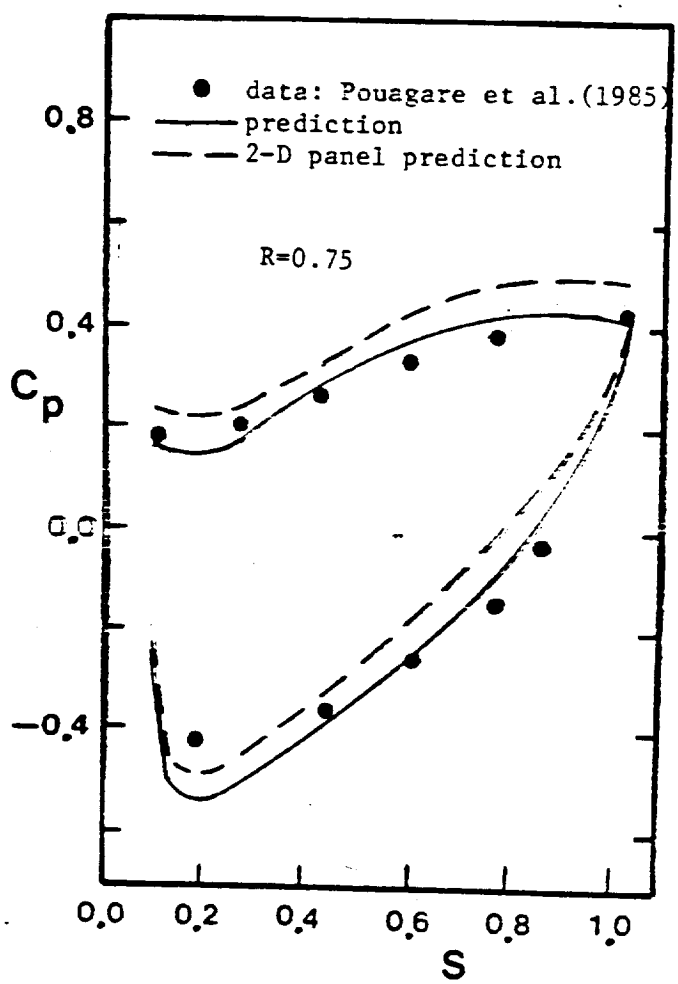

p
d
b
p
p
x
u
p
x
h
Ω
R
N
S
Legend
b blade surface
d downstream
h hub wall
p periodic surface
u upstream
x region of flow which limits stability

SOLUTION TECHNIQUE

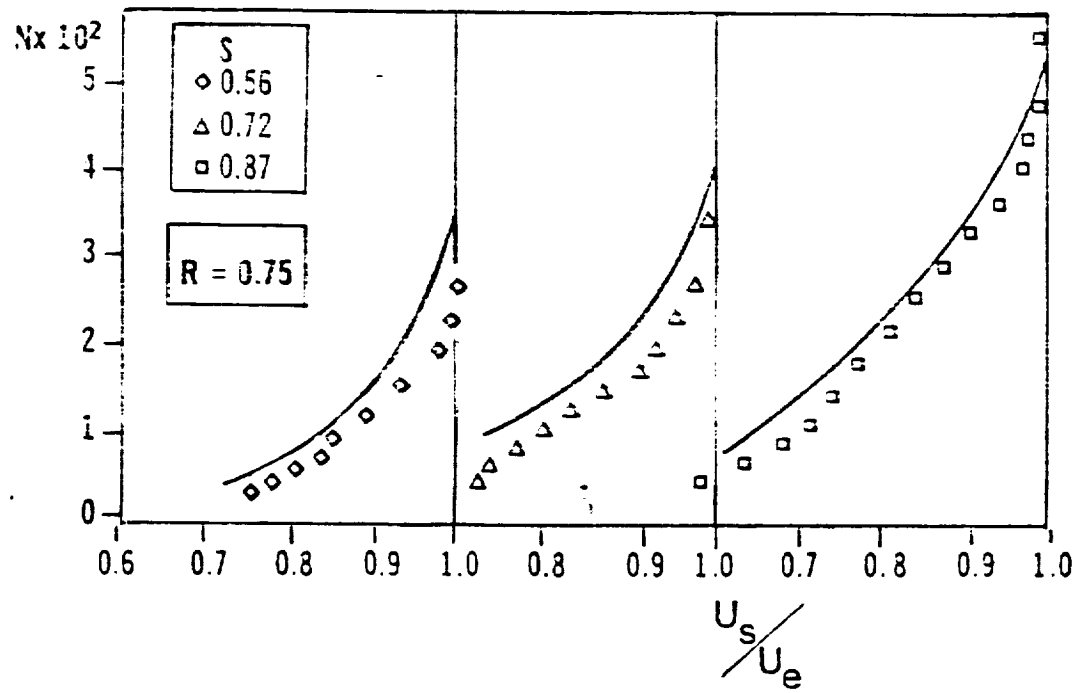
Mean flow equations and two-equation turbulence model (modified INS3D code) solved using Euler implicit solution technique (Beam and Warming Briley and McDonald factorization)

1. Mean flow equations solved at current time-step using eddy viscosity results from previous step
2. Two-equation turbulence model solved at current time-step using current mean flow results
3. Variable coefficient computed at current time-step using current mean and turbulence kinetic energy and dissipation results

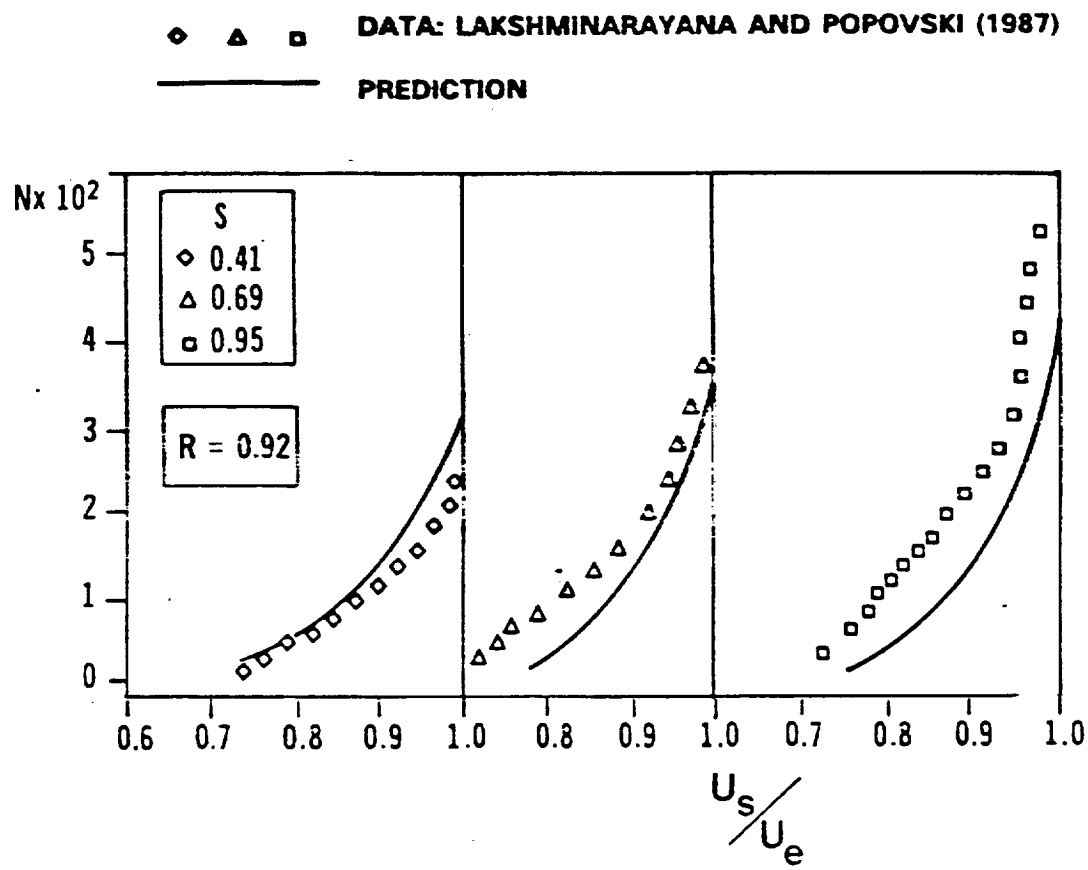
PRESSURE COEFFICIENT AT R=0.75 FOR ϕ=0.56



BOUNDARY LAYER PROFILES ON SUCTION SURFACE. $\phi = 0.50$

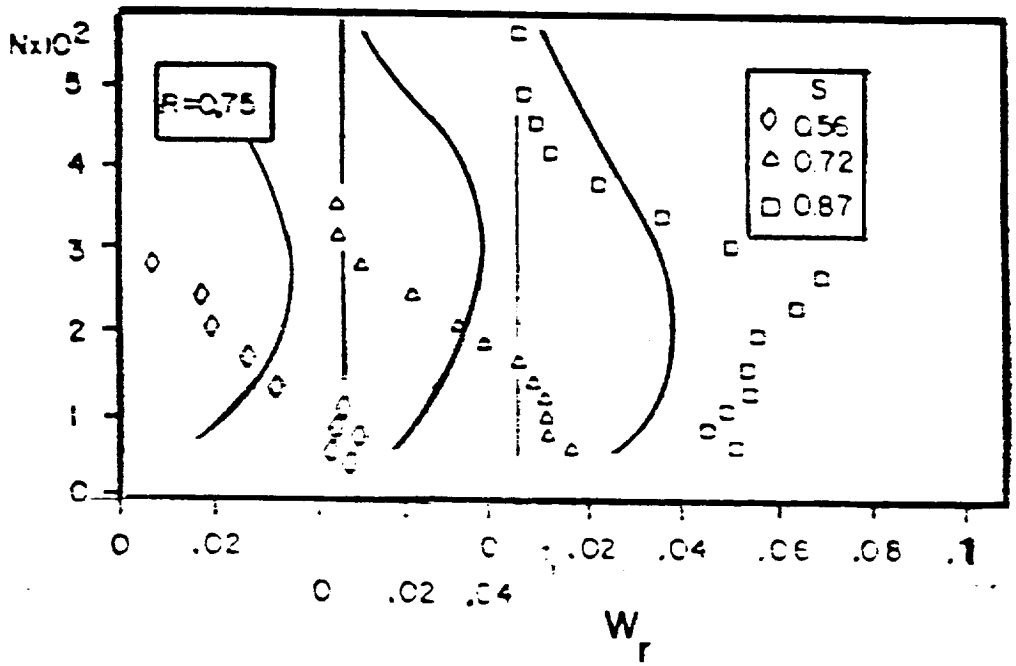


BOUNDARY LAYER PROFILES ON PRESSURE SURFACE, $\phi = 0.50$

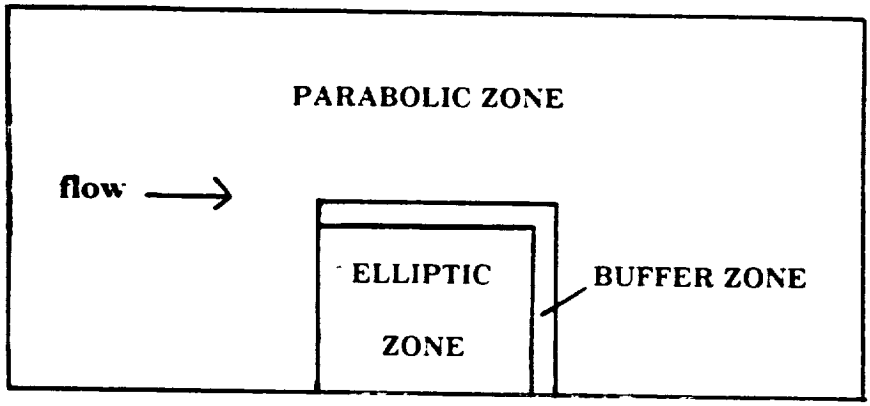


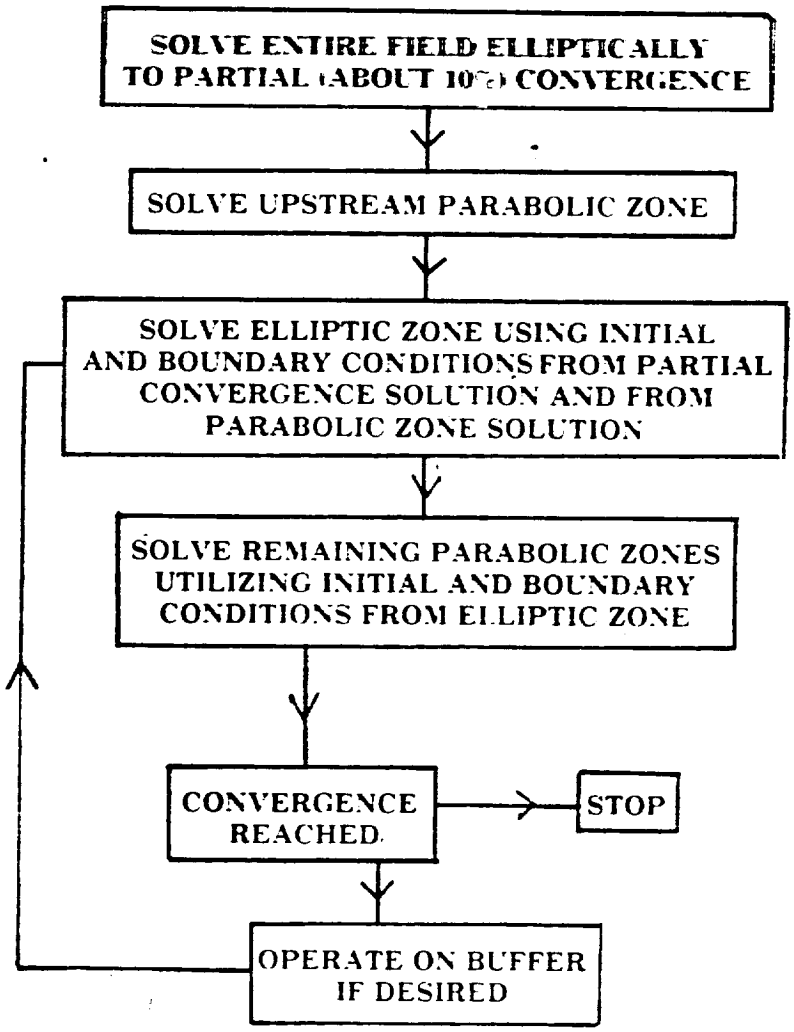
RADIAL VELOCITY ON SUCTION SURFACE, $\phi = 0.50$

19



ZONAL EQUATION METHOD ALGORITHM





NASA CFD VALIDATION MEETING
ISSUE TOPICS FOR INTERNAL FLOWS
AERODYNAMICS AND HEAT TRANSFER

DIFFUSOR AND NOZZLE

- UNIFORM ENTRY FLOW
- NOW UNIFORM ENTRY FLOW
- WHAT DO WE HAVE/WHAT DO WE NEED?

COMBUSTOR

- REACTING/EQUILIBRIUM FLOW
- LOW/HIGH TEMPERATURE
- DATA REQUIREMENTS
- MEASUREMENT TECHNIQUE L2F/LDV/CARS

MODELS

- CURVED DUCT
- ROTATING DUCT
- NEW MODELS TO SIMULATE JET ENGINE REAL FLOWS

CORNER FLOWS/WING BODY COMBINATION

- LOW/HIGH SPEED DATA
- FLOW VISUALIZATION
- LDV/L2F MEASUREMENTS

TURBOMACHINERY (COMPRESSORS AND TURBINES)

- TRANSITION
- SEPARATED FLOWS
- 3D VISCOUS FLOW IN ISOLATED ROTOR PASSAGES (HIGH SPEED/ LOW SPEED)
- TIP CLEARANCE/END WALL DATA IN ROTORS
- MULTISTAGE COMPRESSOR/TURBINE DATA
- DATA FROM HIGH TEMP. TURBINES/COOLING EFFECTS
- BLADE SURFACE/FLOW FIELD MEASUREMENTS
- CASCADES/END WALL MODELLING

TURBULENCE MODELLING

- CURVATURE AND ROTATION EFFECTS
- HEAT TRANSFER/HIGH TEMPERATURE EFFECTS
- FREESTREAM TURBULENCE (!) IN MULTISTAGE ENVIRONMENT
- COOLING/JET IMPINGEMENT EFFECTS

OBJECTIVES OF EXPERIMENTAL RESEARCH

1. UNDERSTAND FLOW / FLUID PHYSICS
2. UNDERSTAND FLUID SYSTEM - (COUPLING OF VARIOUS PHENOMENA / COMPONENTS)
3. DEVELOP & VALIDATE FLOW MODELS

   EXAMPLES: TRANSITION; TURBULENCE; SEPERATION; ROTATION & CURVATURE EFFECTS; HIGH TEMPERATURE EFFECTS

   ETC
4. CALIBRATE CODES
5. VALIDATE CODES

UNIVERSITY RESEARCH

(1) At least one [illegible] IN CATEGORY 1, 2, [illegible]

PLUS (2) ITEMS 4 and/or 5

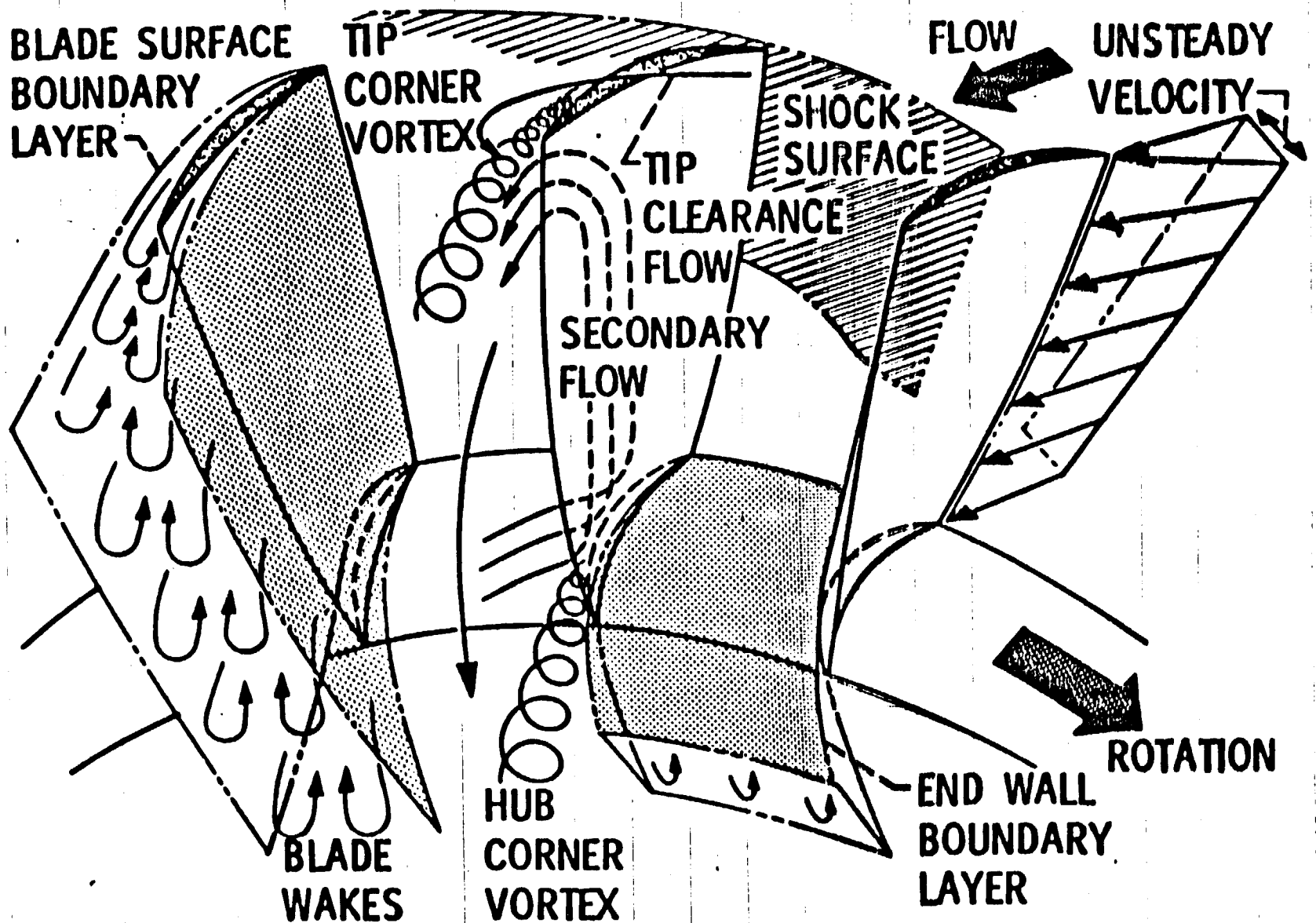


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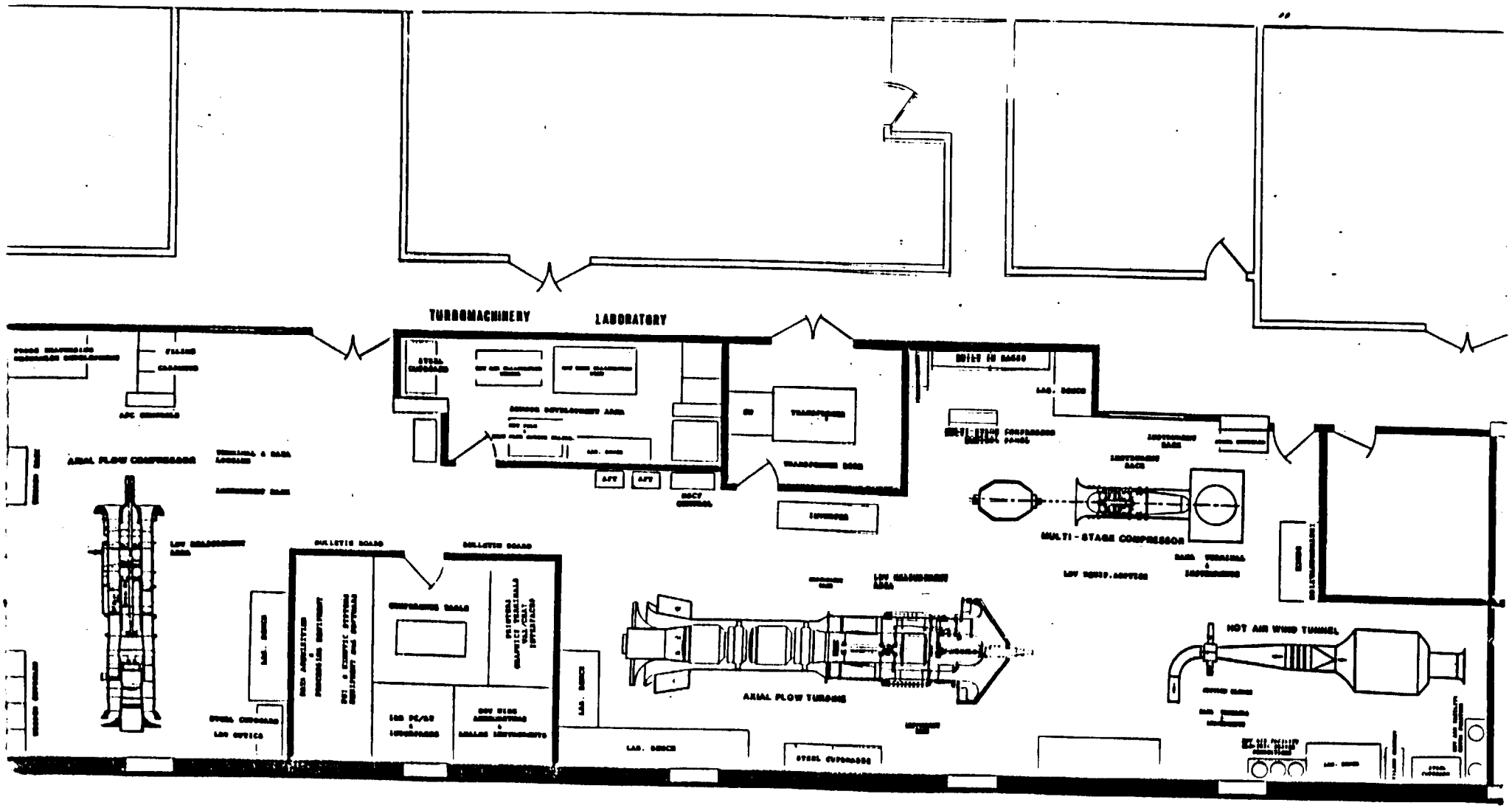
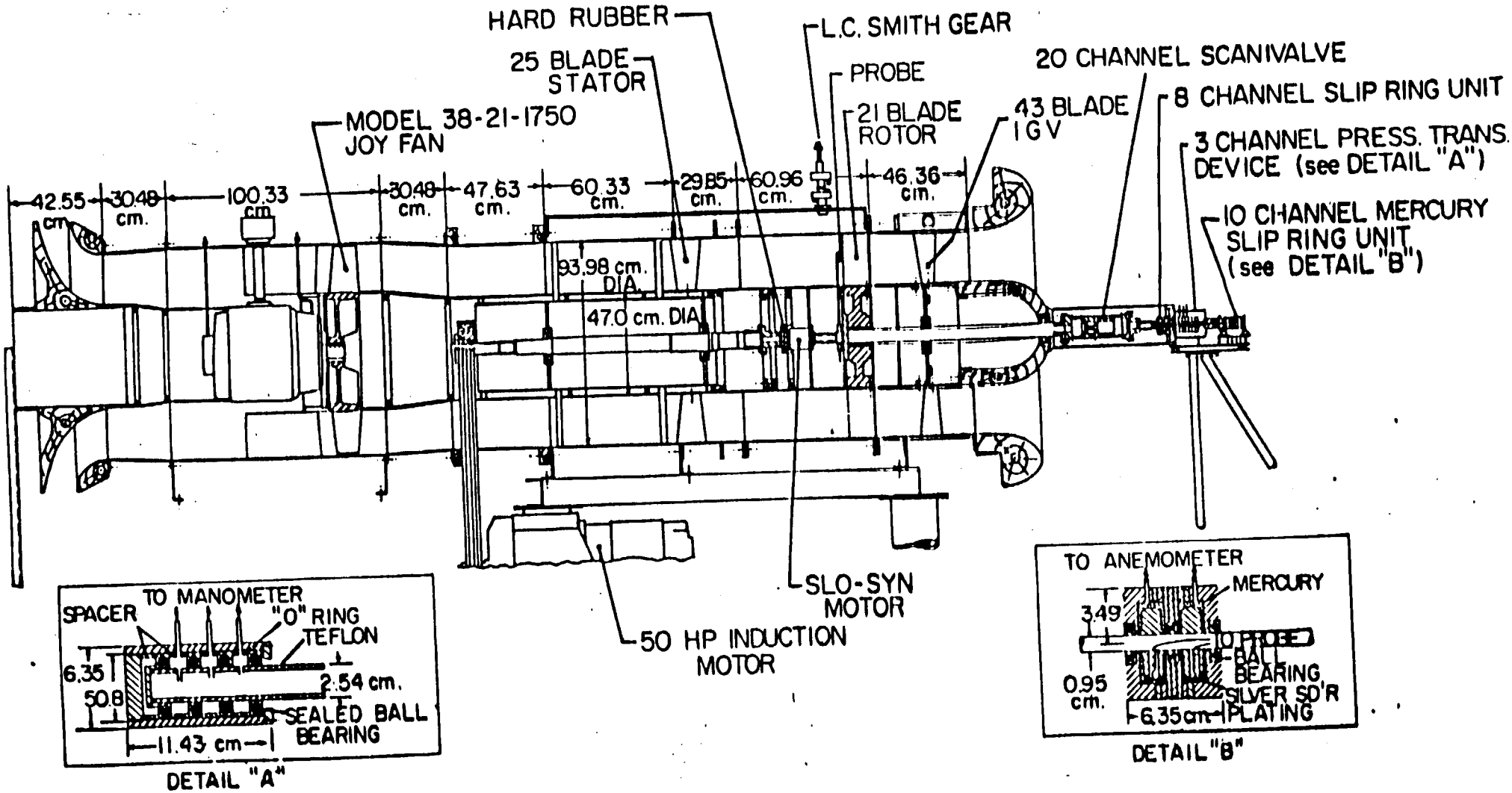
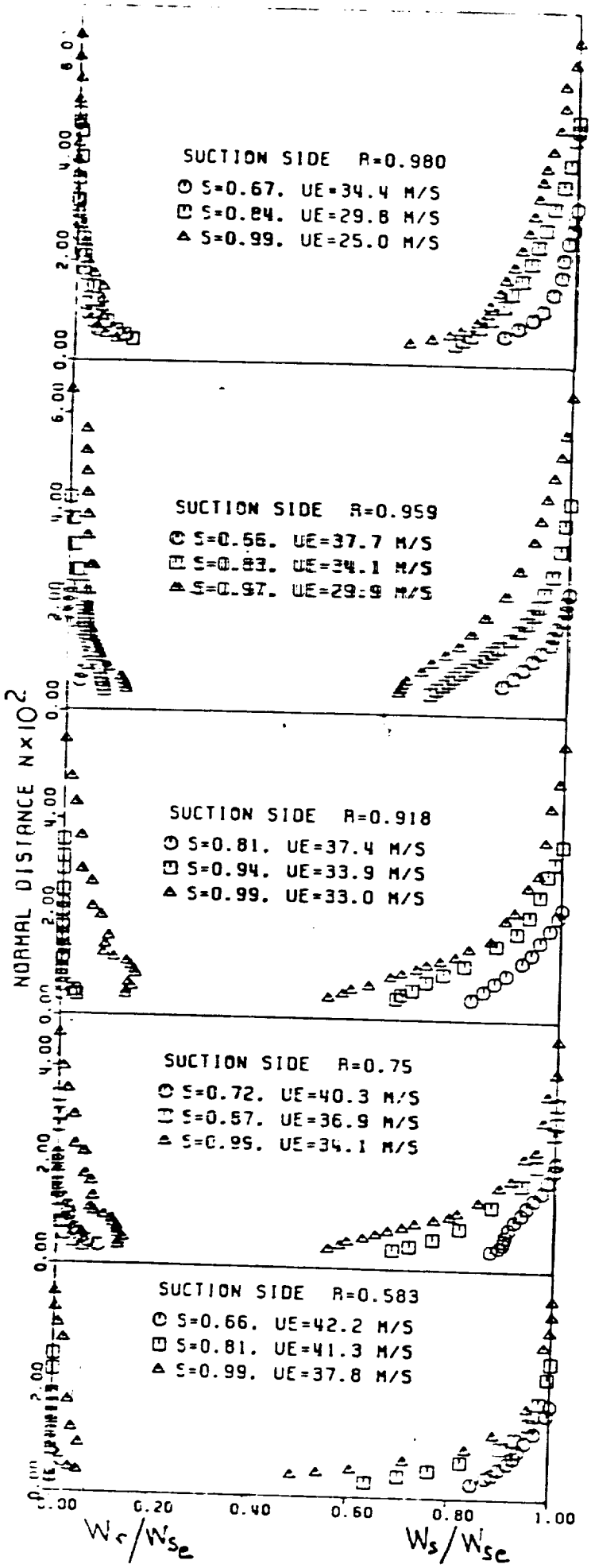
FIG. 2 - TURBOMACHINERY BLADE ROW


TURBOMACHINERY
LABORATORY
AXIAL FLOW COMPRESSOR
MULTI-STAGE COMPRESSOR
AXIAL FLOW TURBINE
HOT AIR WIND TUNNEL


HARD RUBBER
25 BLADE STATOR
L.C. SMITH GEAR
PROBE
20 CHANNEL SCANIVALVE
8 CHANNEL SLIP RING UNIT
MODEL 38-21-1750 JOY FAN
21 BLADE ROTOR
43 BLADE IGV
3 CHANNEL PRESS. TRANS. DEVICE (see DETAIL "A")
10 CHANNEL MERCURY SLIP RING UNIT (see DETAIL "B")
42.55 cm
30.48 cm.
100.33 cm
30.48 cm.
47.63 cm.
60.33 cm.
29.85 cm.
60.96 cm.
46.36 cm.
93.98 cm. DIA.
47.0 cm. DIA.
SLO-SYN MOTOR
50 HP INDUCTION MOTOR
TO MANOMETER
SPACER
"O" RING
TEFLON
6.35
50.8
2.54 cm.
SEALED BALL BEARING
11.43 cm
DETAIL "A"
TO ANEMOMETER
MERCURY
3.49
PROBE
BALL BEARING
SILVER SD'R PLATING
0.95 cm.
6.35 cm
DETAIL "B"


SUCTION SIDE R=0.980
S=0.67. UE=34.4 M/S
S=0.84. UE=29.8 M/S
S=0.99. UE=25.0 M/S
SUCTION SIDE R=0.959
S=0.66. UE=37.7 M/S
S=0.83. UE=34.1 M/S
S=0.97. UE=29.9 M/S
SUCTION SIDE R=0.918
S=0.81. UE=37.4 M/S
S=0.94. UE=33.9 M/S
S=0.99. UE=33.0 M/S
SUCTION SIDE R=0.75
S=0.72. UE=40.3 M/S
S=0.87. UE=36.9 M/S
S=0.99. UE=34.1 M/S
SUCTION SIDE R=0.583
S=0.66. UE=42.2 M/S
S=0.81. UE=41.3 M/S
S=0.99. UE=37.8 M/S
NORMAL DISTANCE N×10²
0.00
2.00
4.00
6.00
0.20
0.40
0.60
0.80
1.00
Wr/Wse
Ws/Wse

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Lab

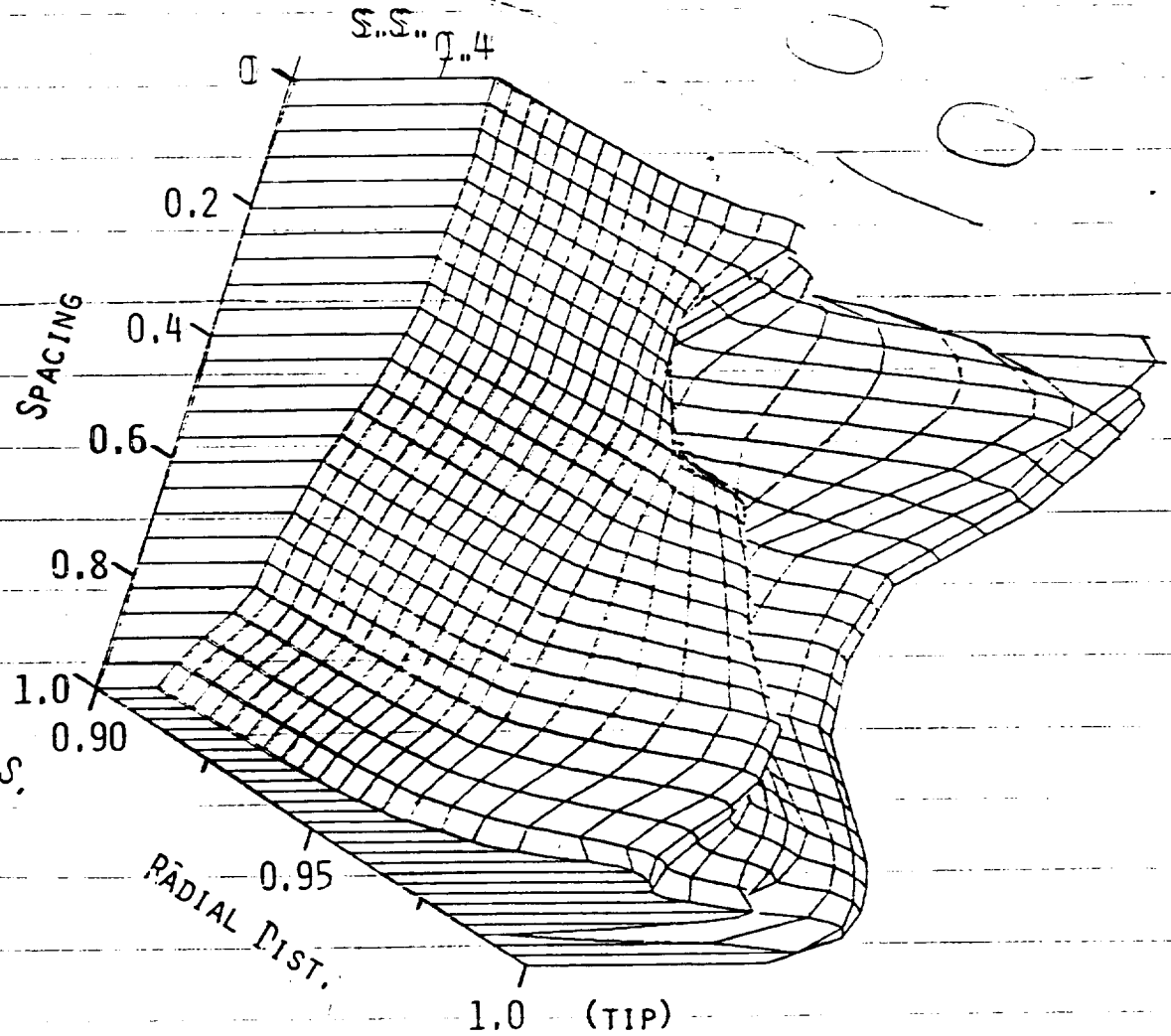
Pressure Field

TANG. VEL TRANSECT AT Z=0.50

PLOT NO. 6 DATE 2/22/84 TIME 22:29:44

AZIM = 25.0 ELEV. = 45.0 DIST = 10000

DAS



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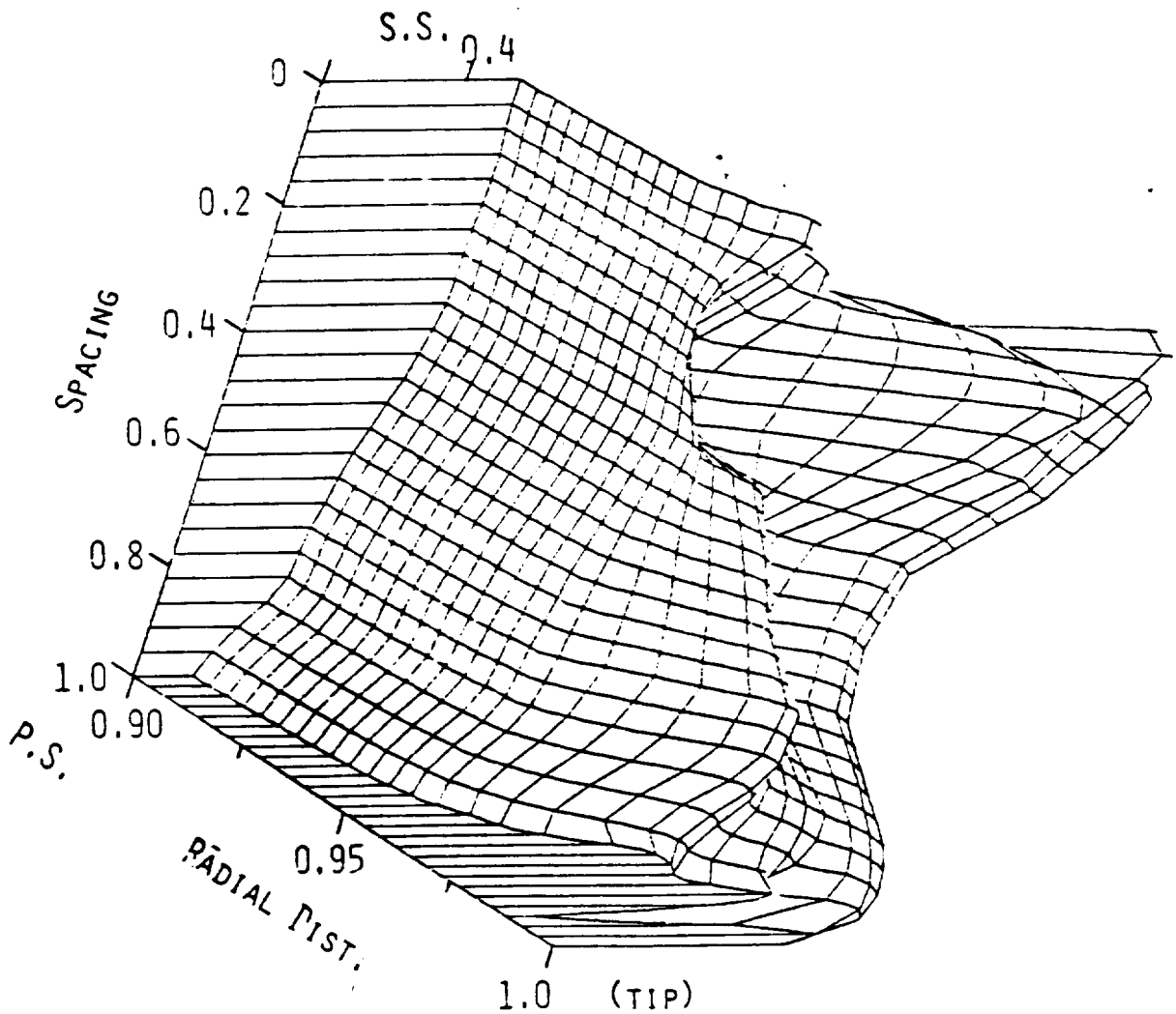
TANG. VEL TRANSECT AT Z=0.50

PLOT NO. 6 DATE 2/22/84 TIME 22:29:44

AZIM = 25.0 ELEV = 45.0 DIST = 10000



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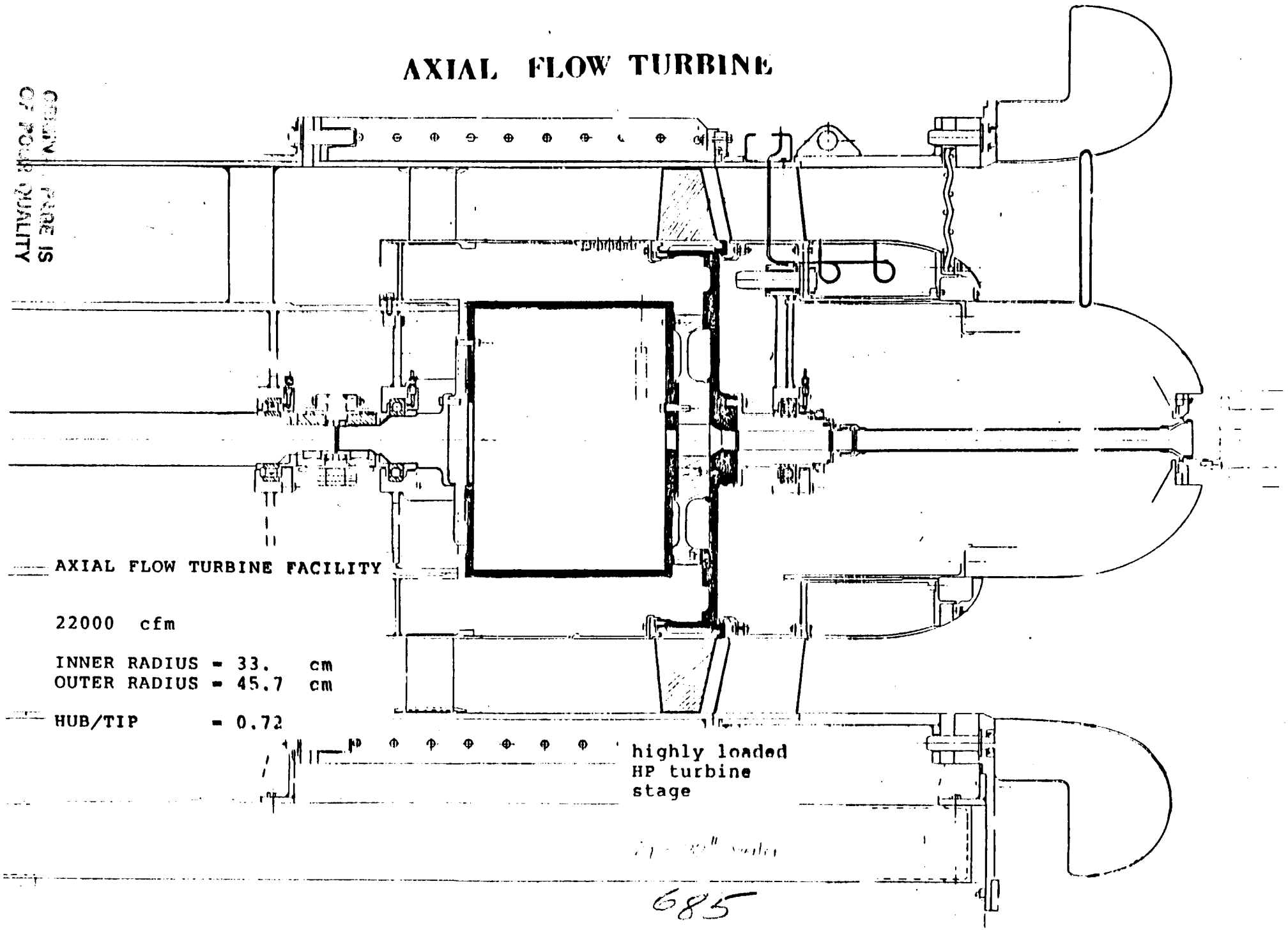
AXIAL FLOW TURBINE



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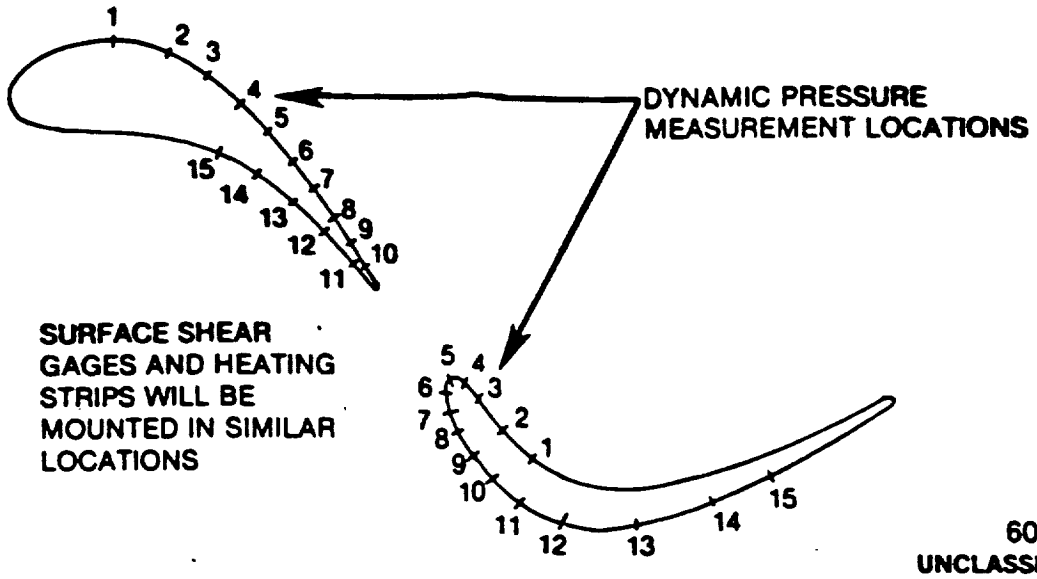
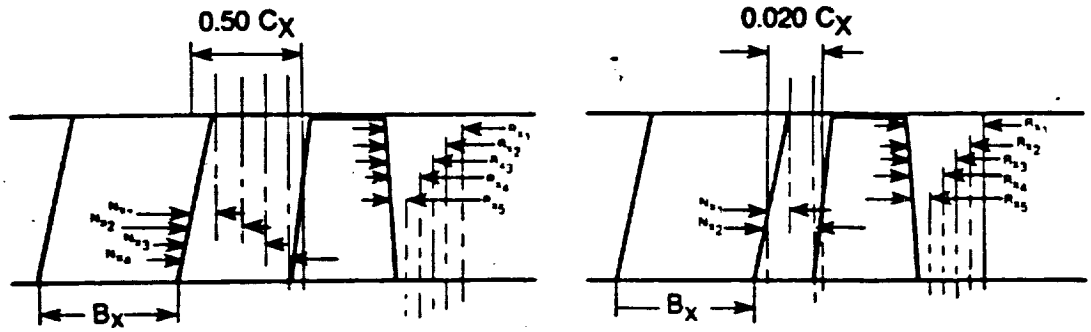


Figure 2.4.22-3 (U) SPECIALIZED INSTRUMENTATION LOCATION: High frequency response instrumentation will be located around the airfoil profiles to ensure sufficient coverage exists in the areas of interest.



SURVEY LOCATIONS	$W_c = 0$		$W_c = a$		$W_c = b$	
	T_1	T_2	T_1	T_2	T_1	T_2
N_{x_1}	O	O	O		O	
N_{x_2}	O	O			O	
N_{x_3}	O	O	O		O	
N_{x_4}	O	O			O	
R_{x_1}	O	O			O	
R_{x_2}	O				O	
R_{x_3}	O	O			O	
R_{x_4}	O				O	
R_{x_5}	O	O			O	

O : DATA TAKEN AT DESIGN POINT
Wc : COOLING FLOW
T : TURBULENCE INTENSITY

SURVEY LOCATIONS	$W_c =$		$W_c = a$		$W_c = b$	
	T_1	T_2	T_1	T_2	T_1	T_2
N_{x_1}	O□	O	O		O□	
N_{x_2}	O□	O			O□	
R_{x_1}	O□				O□	
R_{x_2}	O□					
R_{x_3}	O□				O□	
R_{x_4}	O□					
R_{x_5}	O□				O□	

O DATA AT DESIGN POINT
□ DATA AT PART POWER PO
COOLING FAN
TURBULENCE INTENSITY

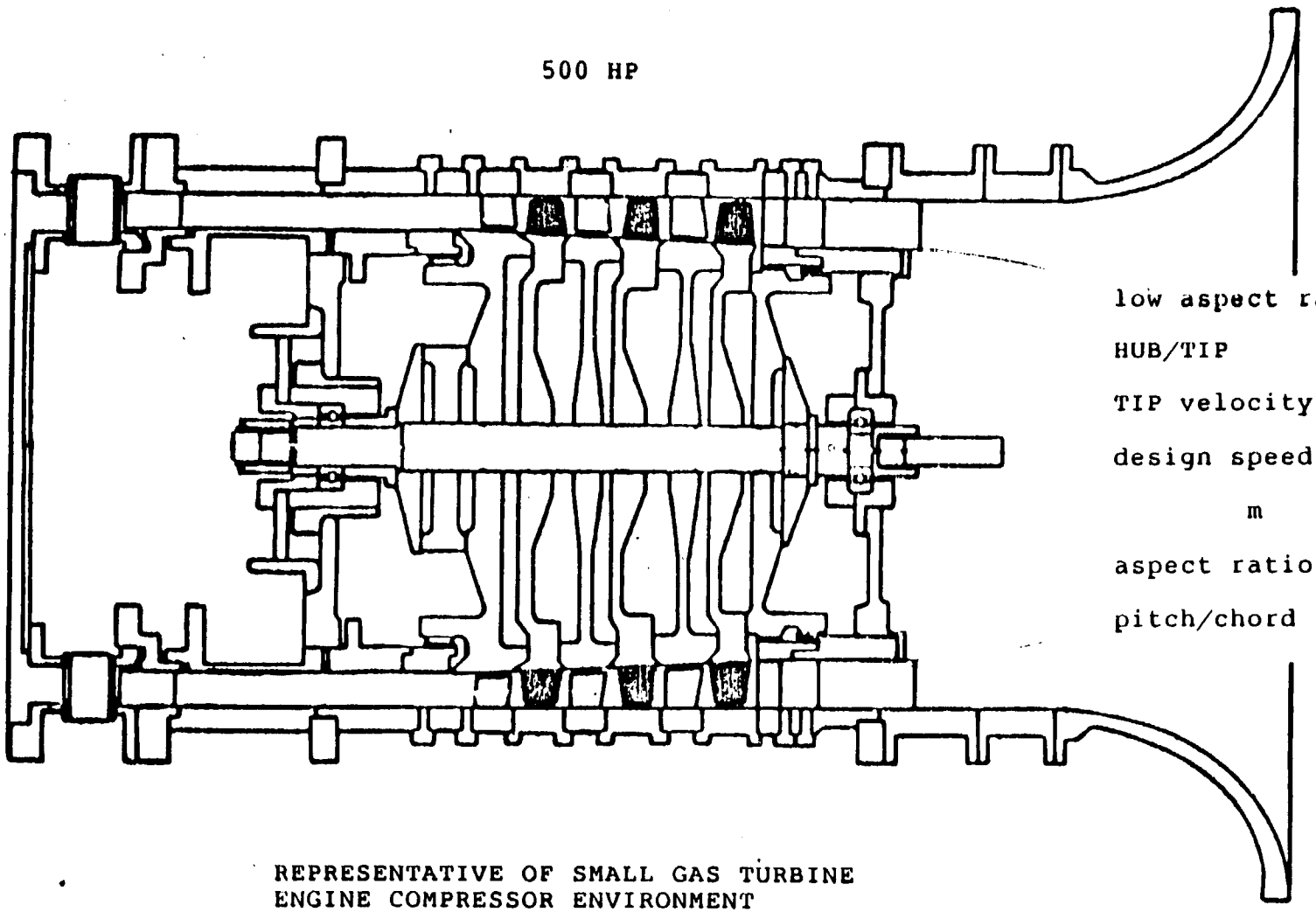
60596
UNCLASSIFIED

Figure 2.4.22-4 (U) EXPERIMENTAL PROGRAM TEST MATRIX: Data will be obtained from surface instrumentation and survey probes at various cooling flow levels, turbulence levels and operating points.

ASSIFIED

MULTI STAGE COMPRESSOR

500 HP



low aspect ratio

HUB/TIP = 0.842

TIP velocity = 200 m/sec

design speed = 5410 rpm

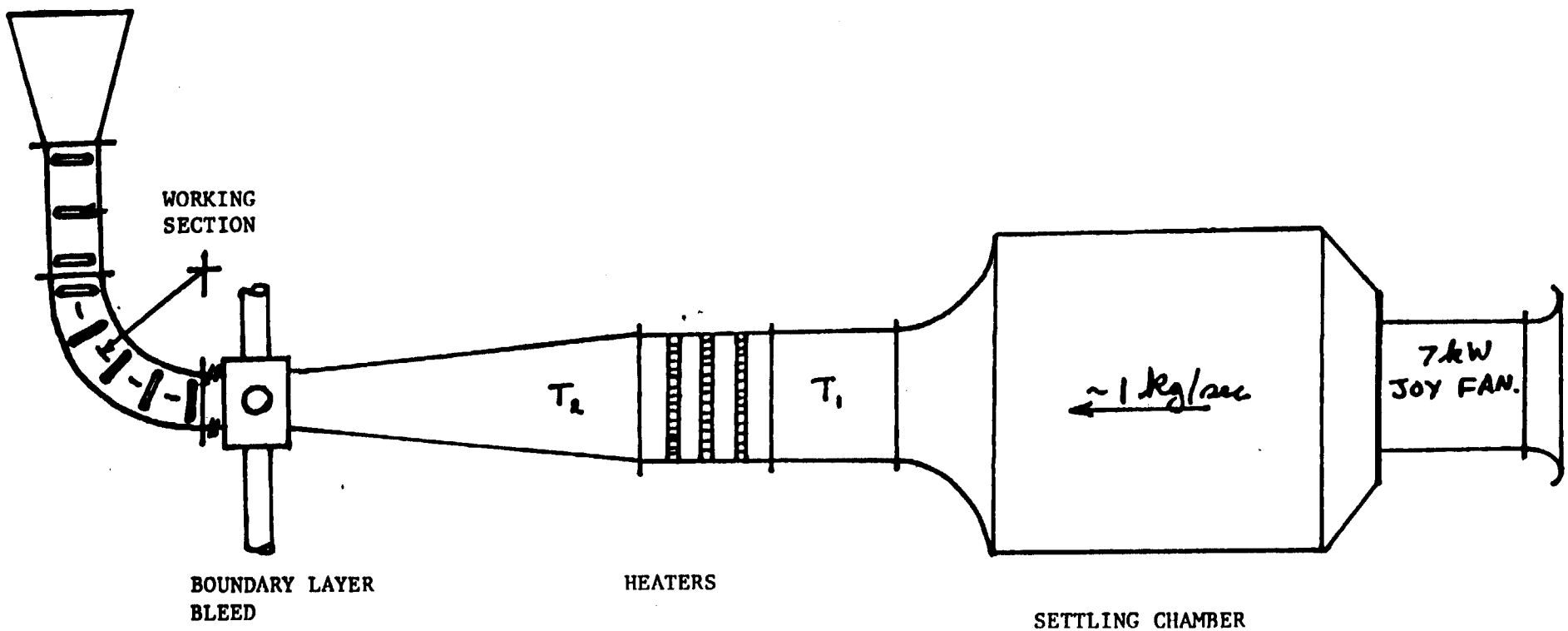
m = 9.45 kg/sec

aspect ratio = 1.43 ... 1.63

pitch/chord = 1.2 ... 1.27

REPRESENTATIVE OF SMALL GAS TURBINE
ENGINE COMPRESSOR ENVIRONMENT

Fig.1 HEAT TRANSFER FACILITY



HEATED CURVED DUCT EXPERIMENT

WORKING SECTION GEOMETRY SPECIFICATIONS:

- CROSS SECTIONAL AREA: - 8" x 8"
- DUCT CENTERLINE RADIUS OF CURVATURE: - 12"
- INNER WALL RADIUS OF CURVATURE: - 8"
  OUTER WALL RADIUS OF CURVATURE: - 15"
- TURNING ANGLE: - 90^{0}
  (FOLLOWED BY 1 FT. STRAIGHT SECTION)
- MEASUREMENT LOCATIONS SPACED AT 22.5^{0}
  (AROUND CURVATURE OF DUCT)

  - SLOTS FOR HOT WIRE PROBE ACCESS AND TO ACCOMMODATE A LDV QUARTZ WINDOW

  - 20 STATIC PRESSURE, SKIN FRICTION AND WALL TEMPERATURE MEASUREMENTS (FIVE PER WALL) AT EACH MEASUREMENT LOCATION

ON GOING / PROPOSED AERODYNAMIC EXPERIMENTS

- 3D INVISCID/VISCID FLOW IN TURBINE NOZZLES & ROTORS INCLUDING ENDWALL FLOWS, BLADE BOUNDARY LAYERS & WAKES

- ROTOR/STATOR INTERACTION (2 spacings) IN TURBINES
  - unsteady pressure/shear stress/transition on rotor blades
  - unsteady flow field in rotors
  - unsteady blade boundary layers
  - nozzle wake transport

- 3D VISCOUS FLOW MEASUREMENT IN MULTI STAGE COMPRESSORS
  - steady/unsteady flow in 2nd and 3rd stages
  - rotor/stator interaction
  - annulus & hub wall boundary layer development

- THERMAL DRIVEN SECONDARY FLOW IN A 90 DEG. DUCT
  - LDV/hot wire flow measurement
  - optical flow visualization

- 3D BOUNDARY LAYER/HORSE SHOE VORTEX DEVELOPMENT
- 3D SEPARATION IN NOZZLE ENDWALL
- WALL-CYLINDER INTERACTION REGIONS

- 3D VISCOUS FLOW IN SINGLE STAGE COMPRESSOR WITH CDA/E3 BLADES

- LDV MEASUREMENT OF 3D VISCOUS FLOW. IN CENTRIFUGAL COMPRESSORS

- TIP CLEARANCE EFFECTS IN TURBINE ROTORS

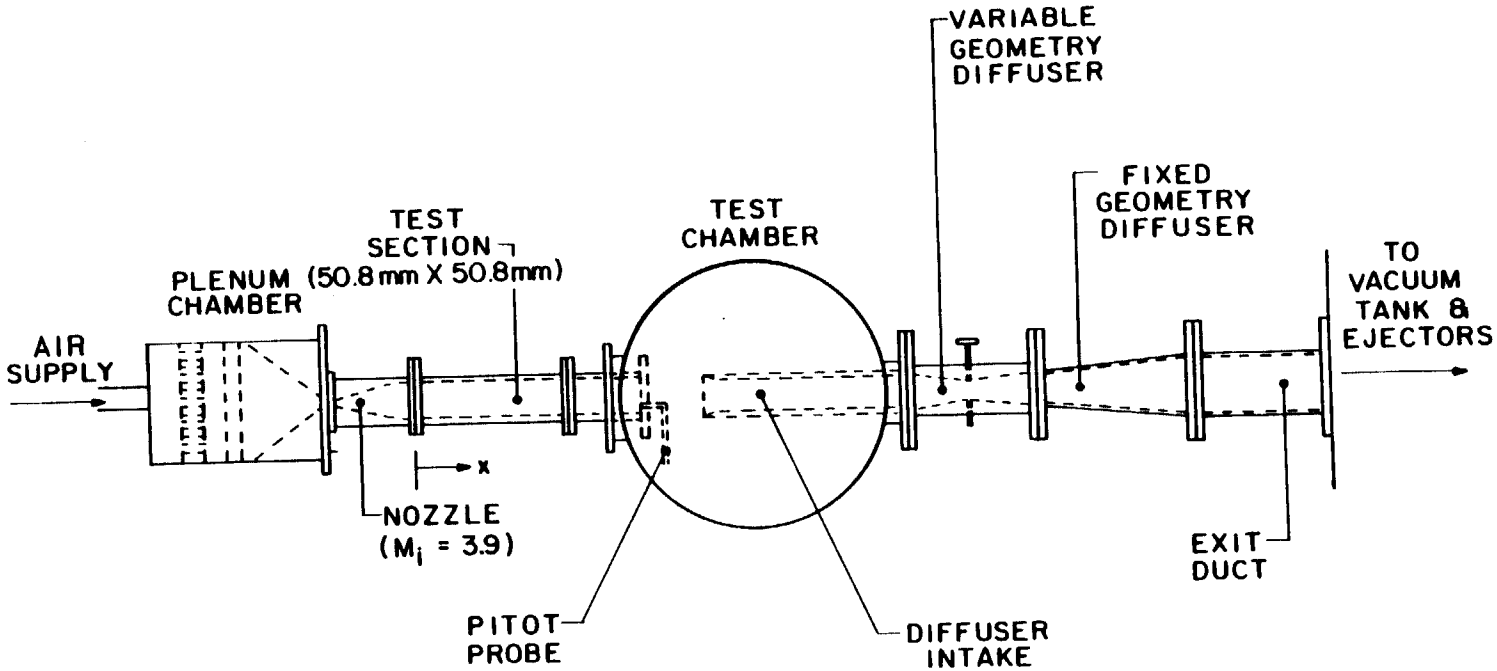
- WALL CYLINDER INTERACTION REGIONS

Gessner

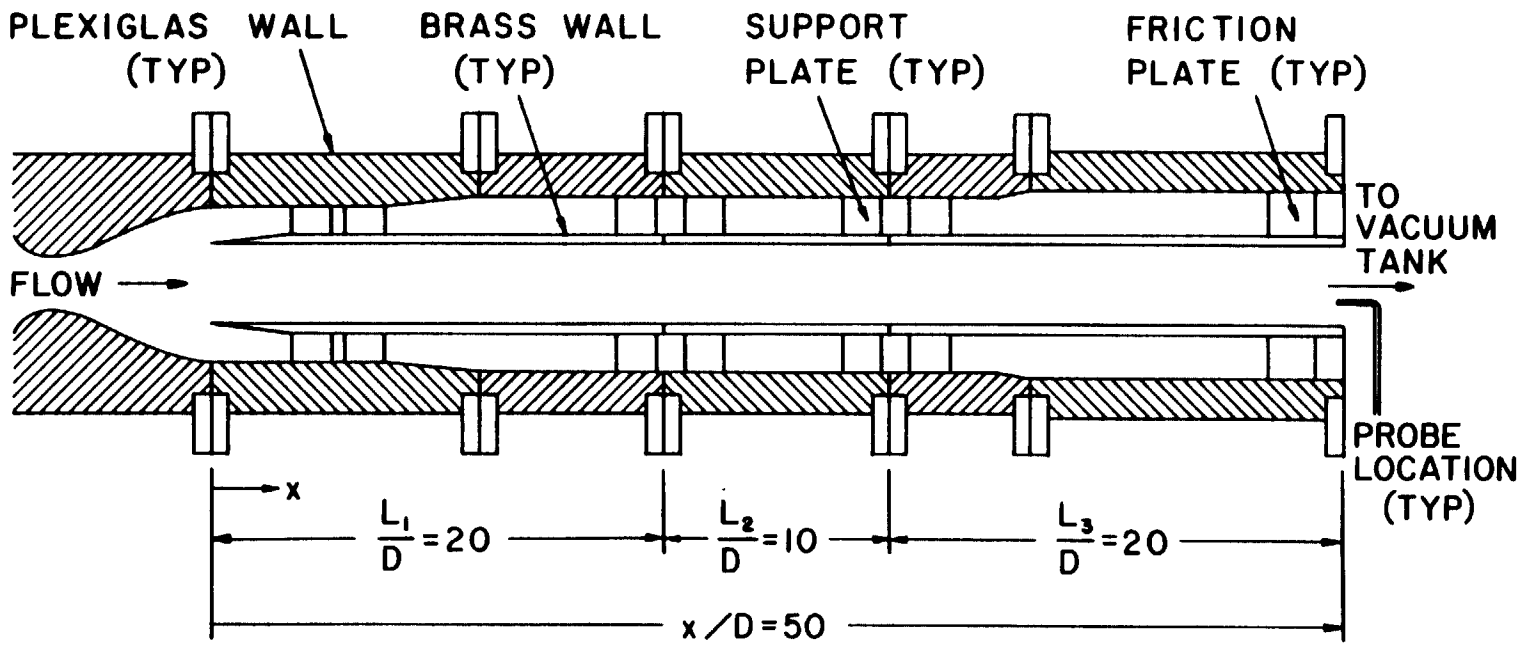
N92-70950

RESEARCH ON COMPLEX TURBULENT FLOWS AT THE UW
(OVERALL EFFORT)

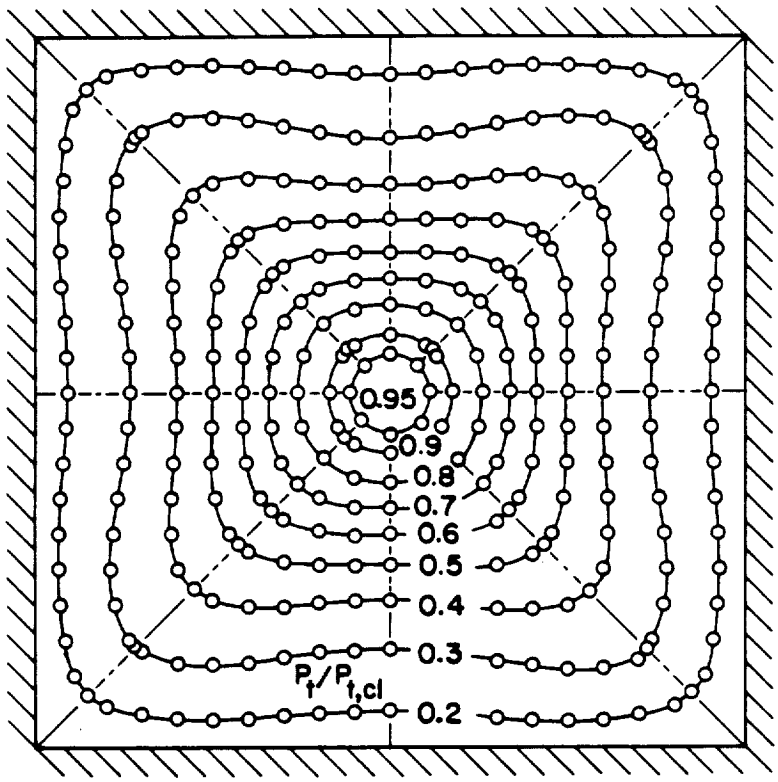
- Development of a pressure-strain model, an algebraic stress model, and wall functions appropriate for flows with spanwise variations in the local wall shear stress (streamwise corner flows, flows with embedded vortices, etc.)
- Development of a hot-wire measurement technique for determining the local mean velocity (3 components) and Reynolds stresses (6 components) in a complex flow when the local mean velocity is arbitrarily skewed in pitch and yaw relative to the probe body
- Experiments on supersonic and subsonic turbulent flow development in a square duct (supersonic work formerly funded by NASA-Ames; subsonic work formerly funded by NSF)
- Experiments on flow about a strut-endwall (wing-body) configuration (funded by NASA-Lewis)
- Experiments on flow within a transition duct (funded by NASA-Lewis)
- Experiments on co-flowing annular jets with swirl (funded by AFOSR)



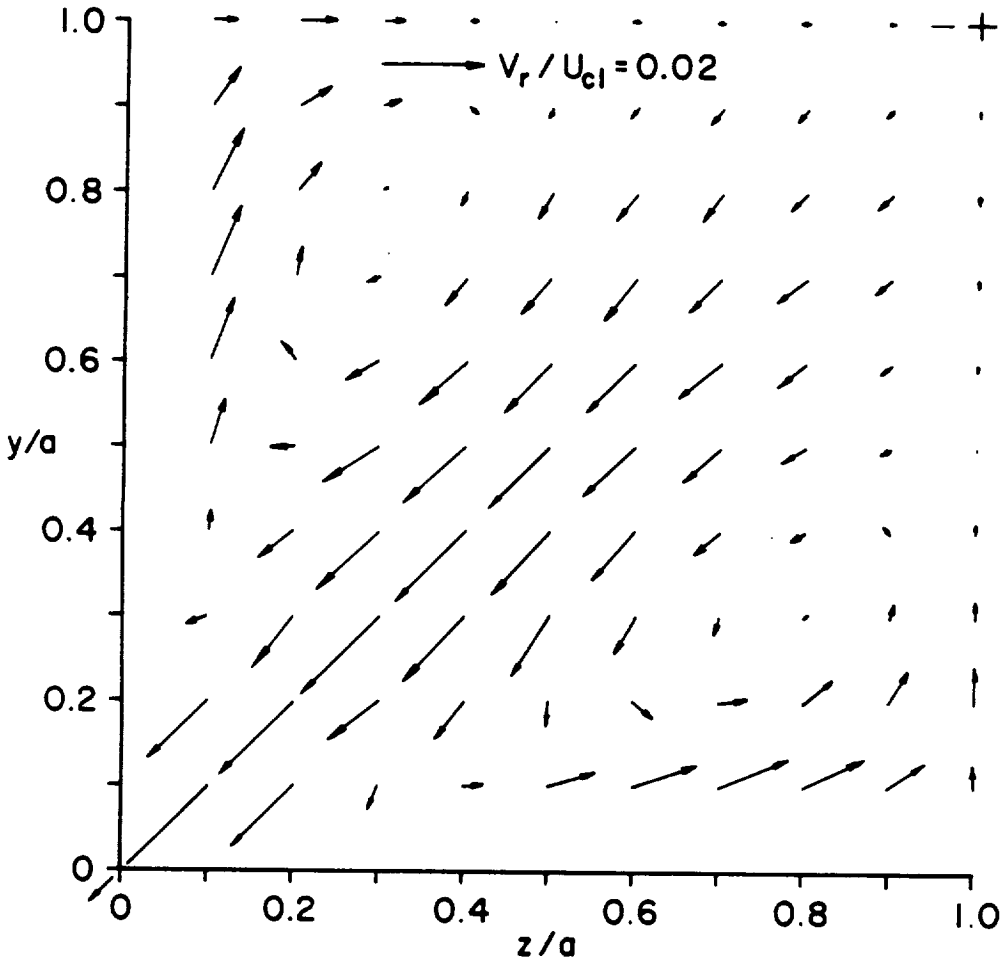
SUPERSONIC CORNER FLOW FACILITY



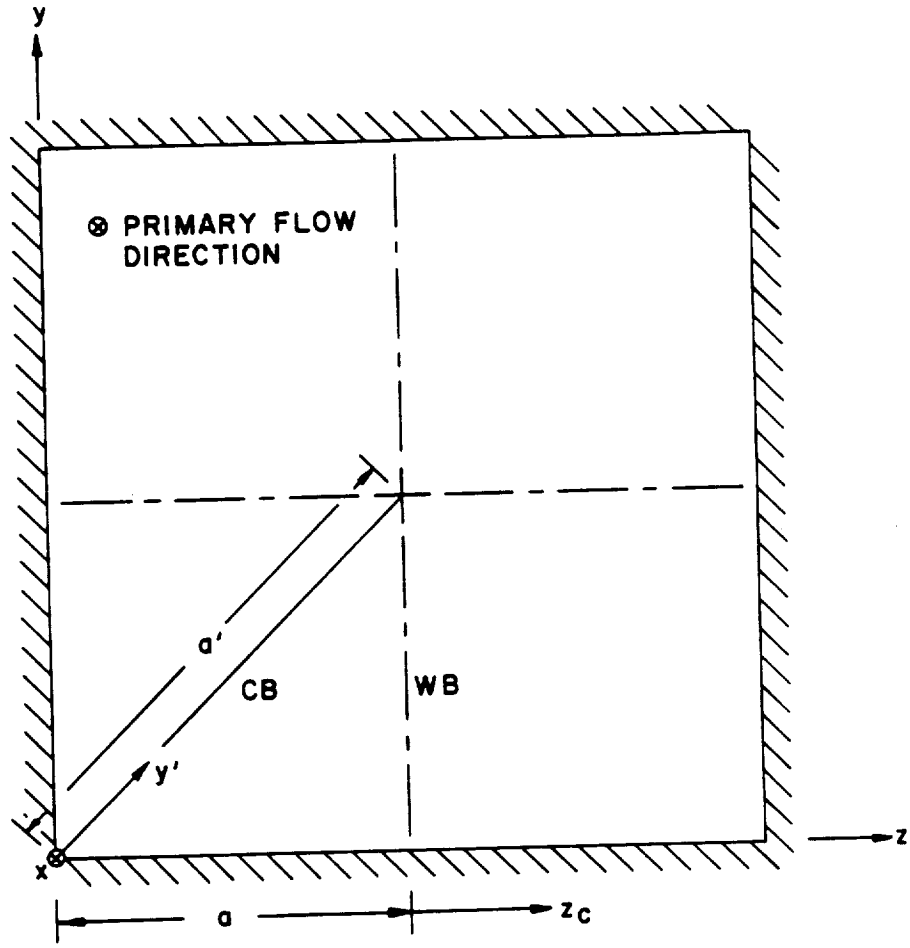
TEST SECTION



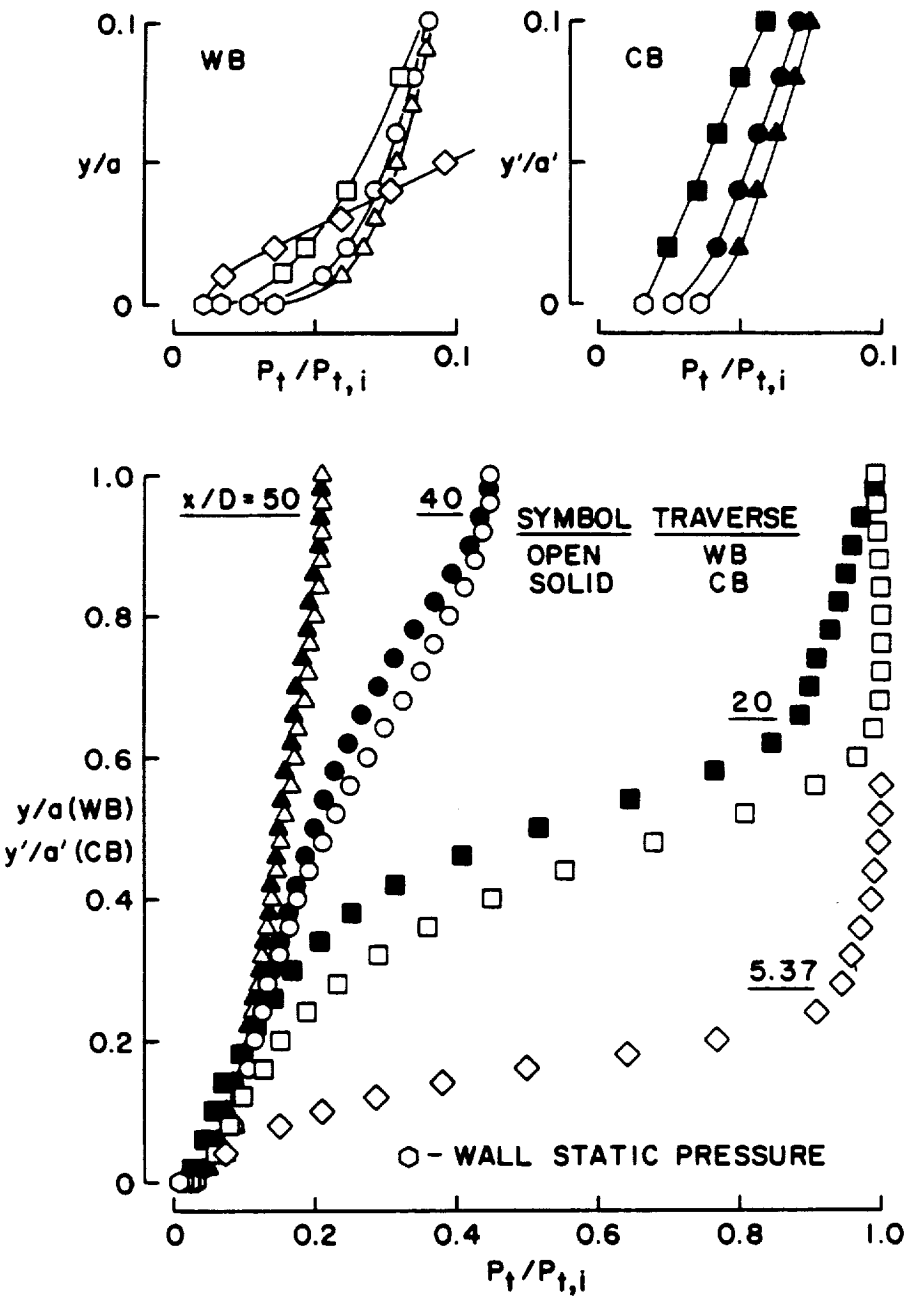
TOTAL PRESSURE CONTOURS AT x/D = 40



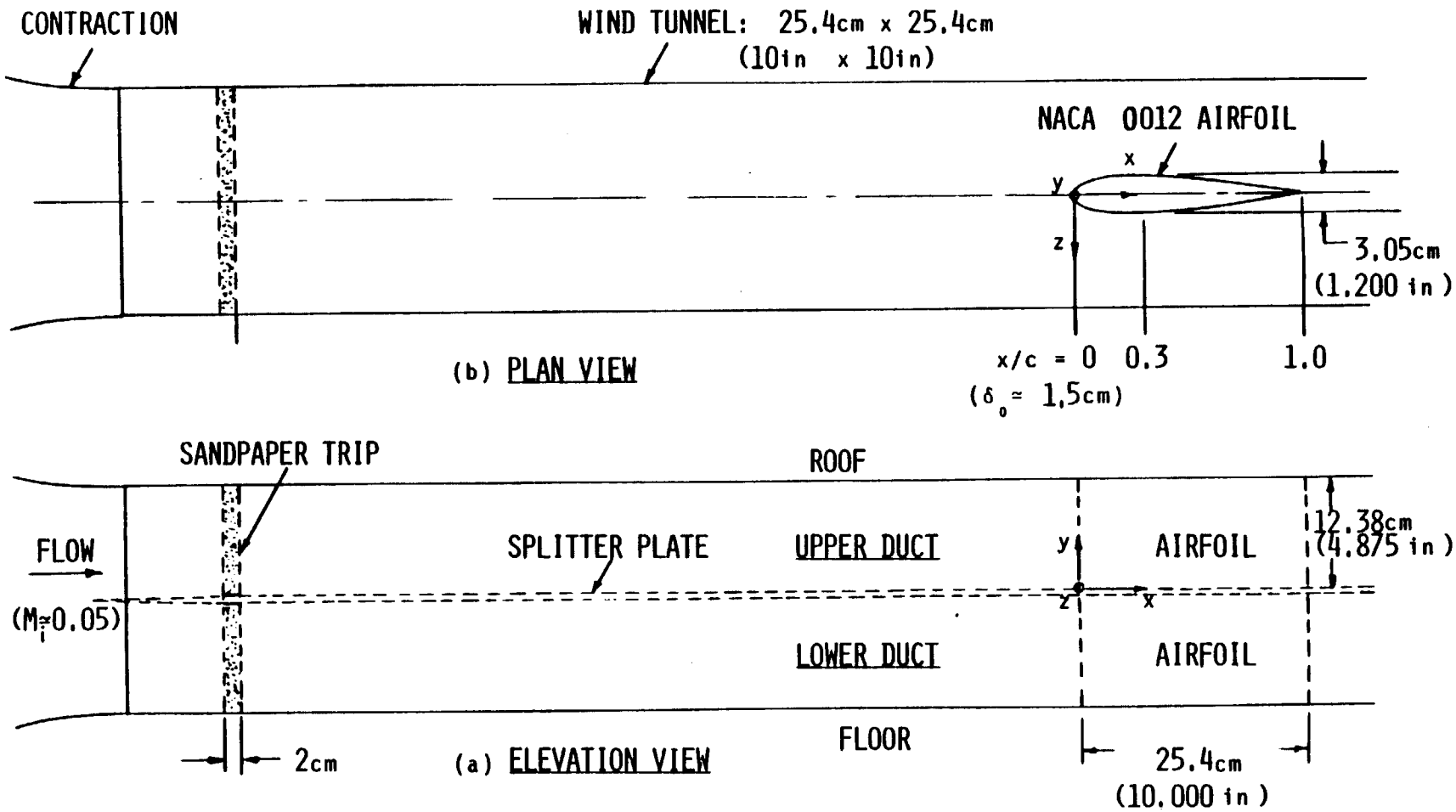
TRANSVERSE FLOW VECTORS AT x/D=50:Probes A&B



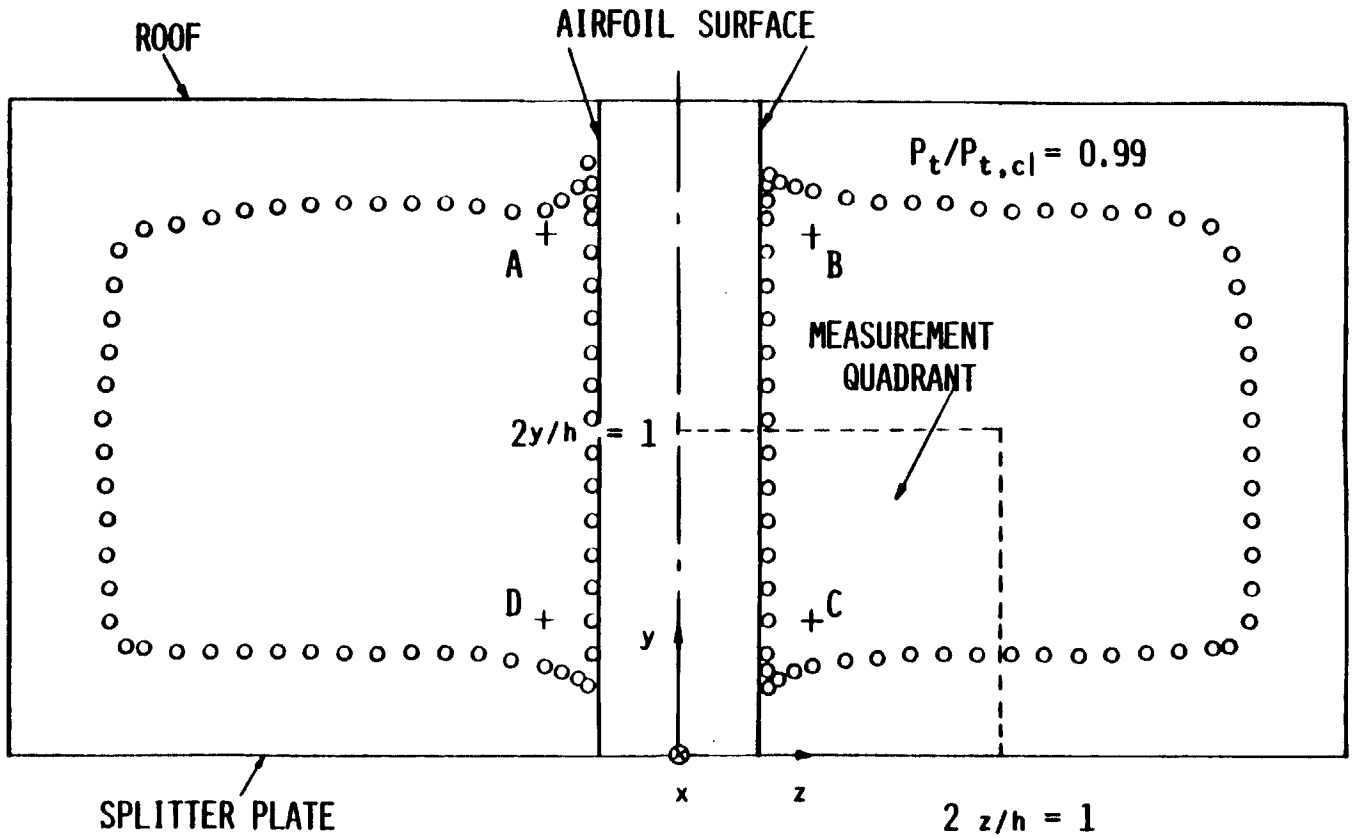
REFERENCE COORDINATES



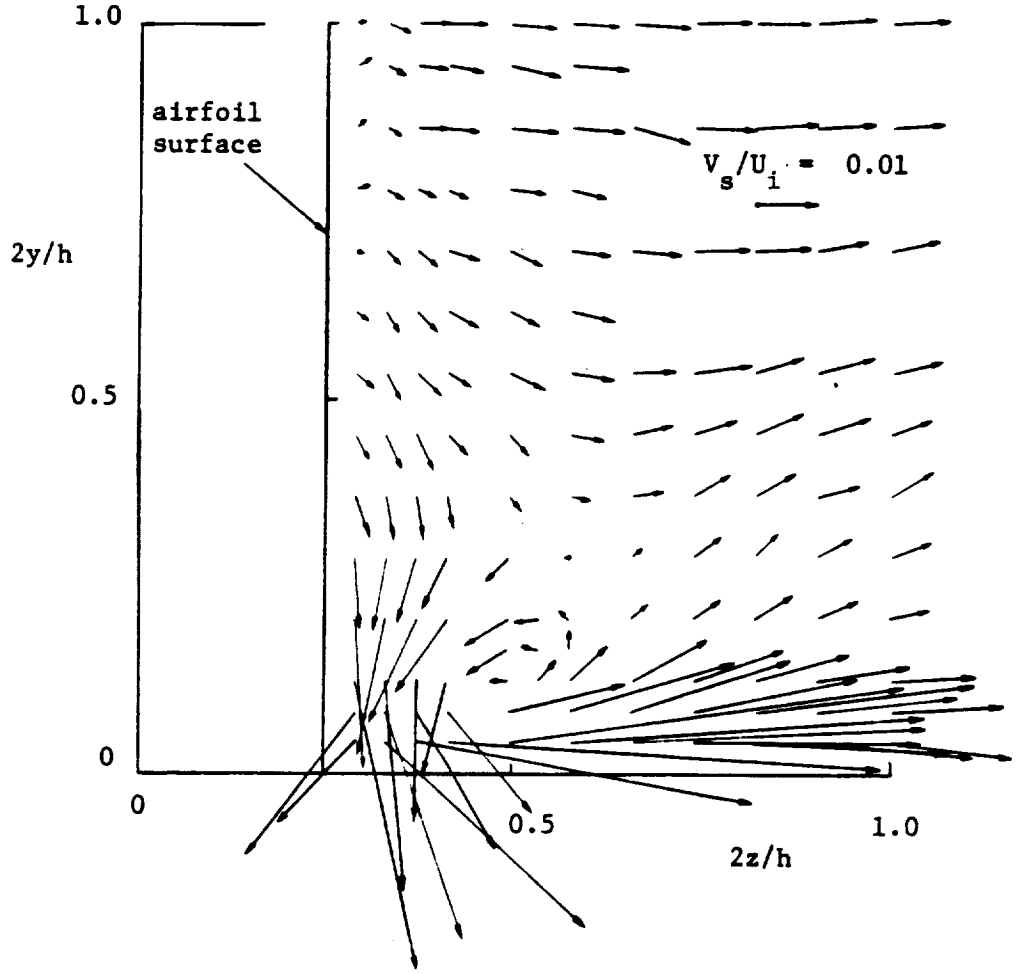
TOTAL PRESSURE PROFILES



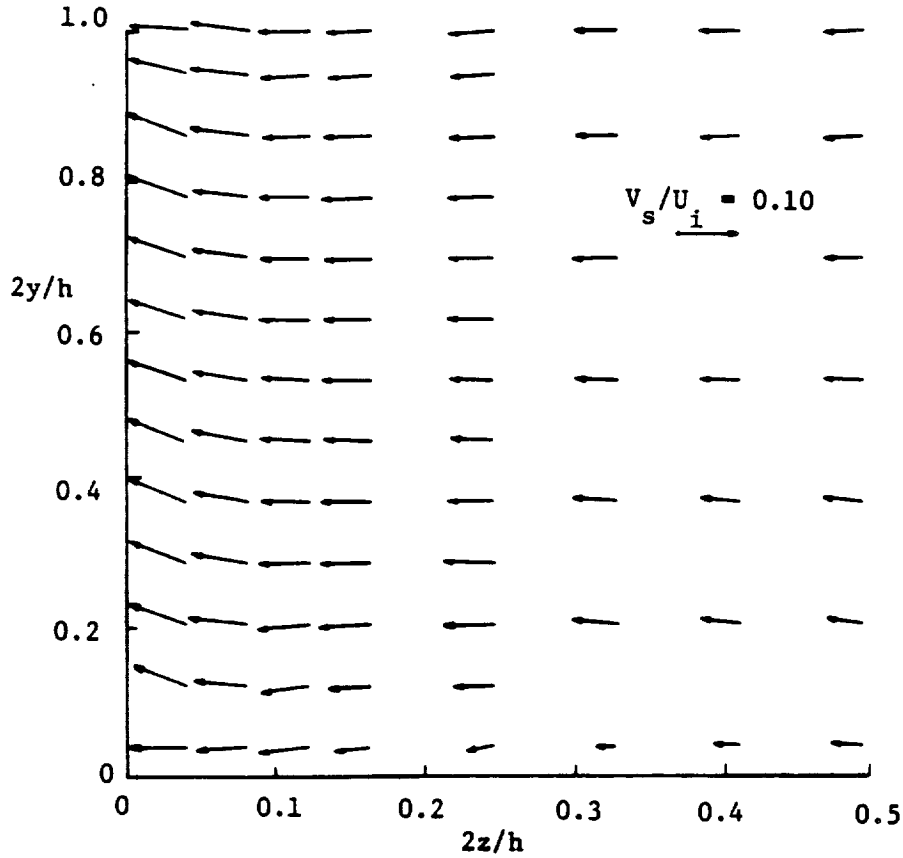
TEST SECTION CONFIGURATION



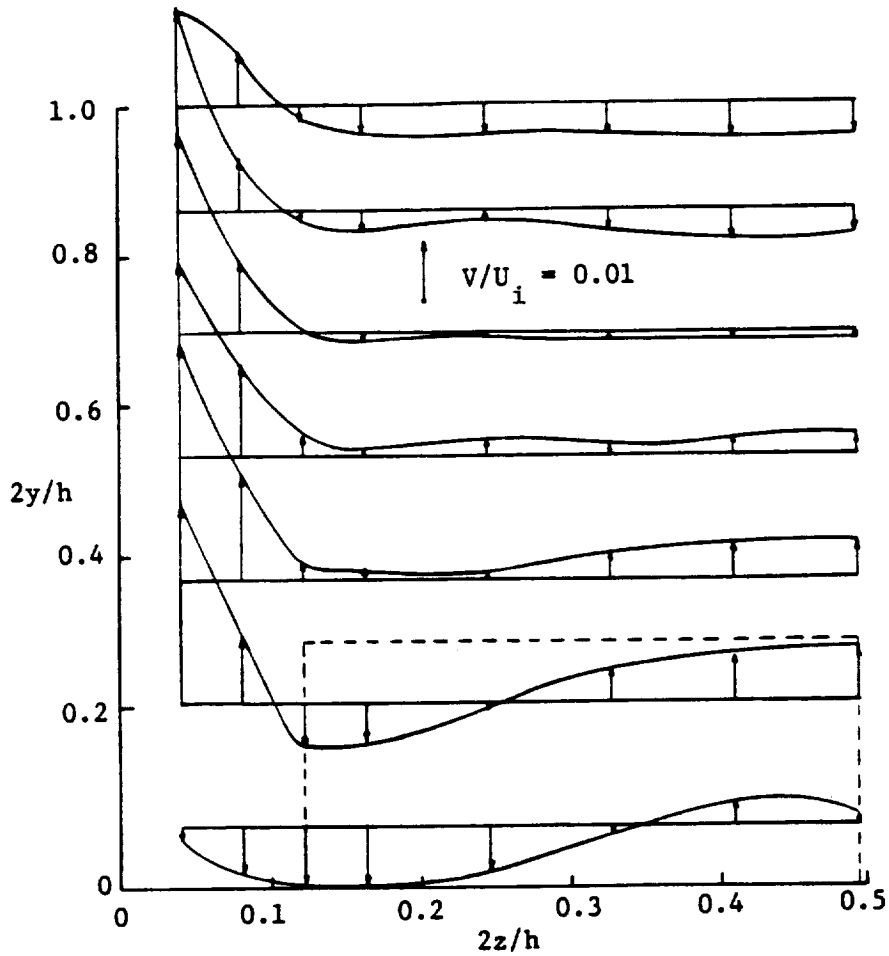
TOTAL PRESSURE CONTOURS ACROSS UPPER DUCT
CROSS SECTION TO CHECK FLOW SYMMETRY AT x/c = 0.3
(INITIAL STATION AT MAXIMUM AIRFOIL THICKNESS)



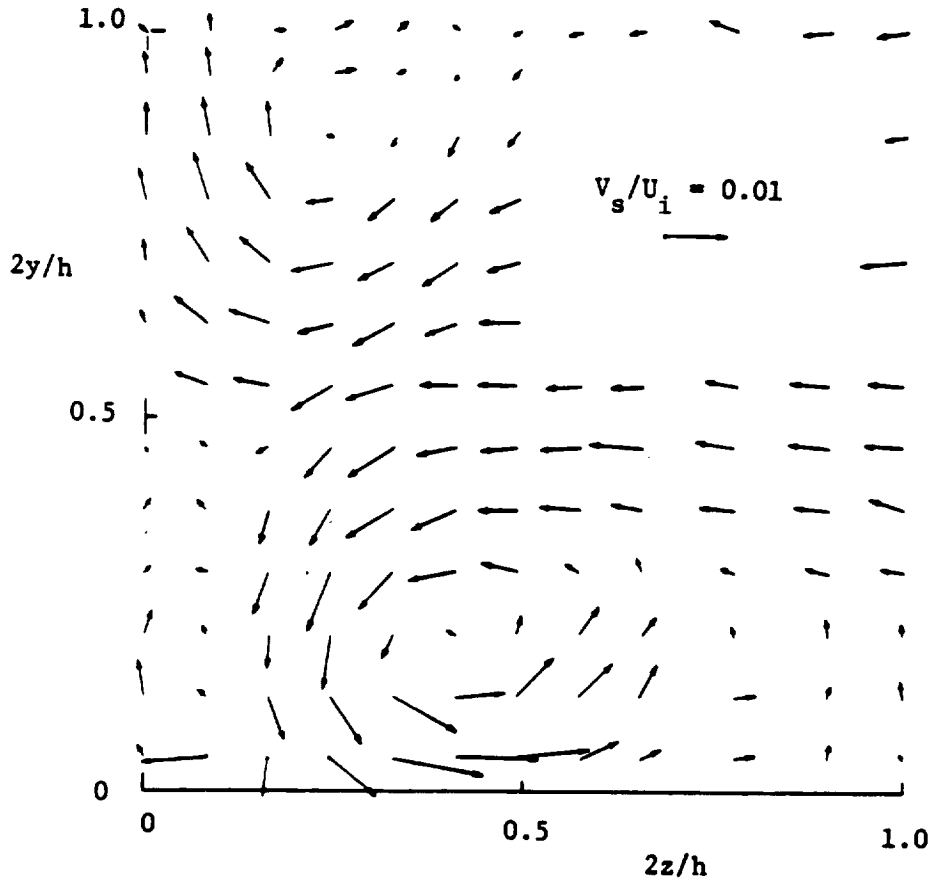
RESULTANT TRANSVERSE MEAN VELOCITY PATTERN AT MAXIMUM AIRFOIL THICKNESS (x/c = 0.3)



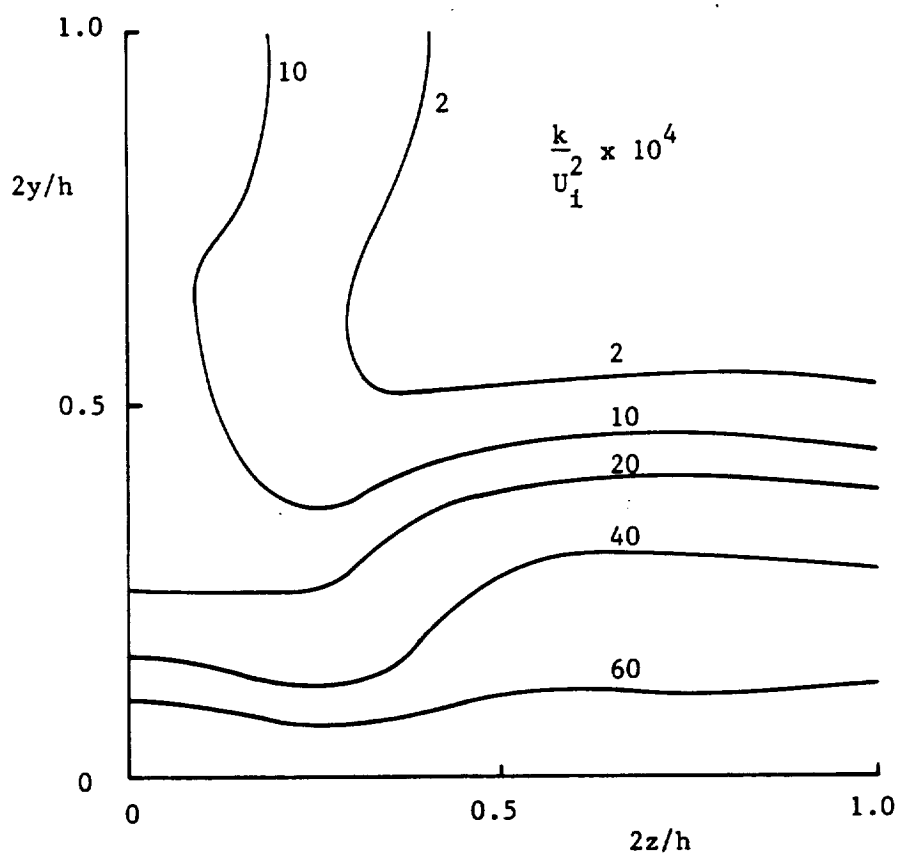
TRANSVERSE MEAN VELOCITY PATTERN AT x/c = 1.0
(RESULTANT COMPONENT BEHAVIOR)



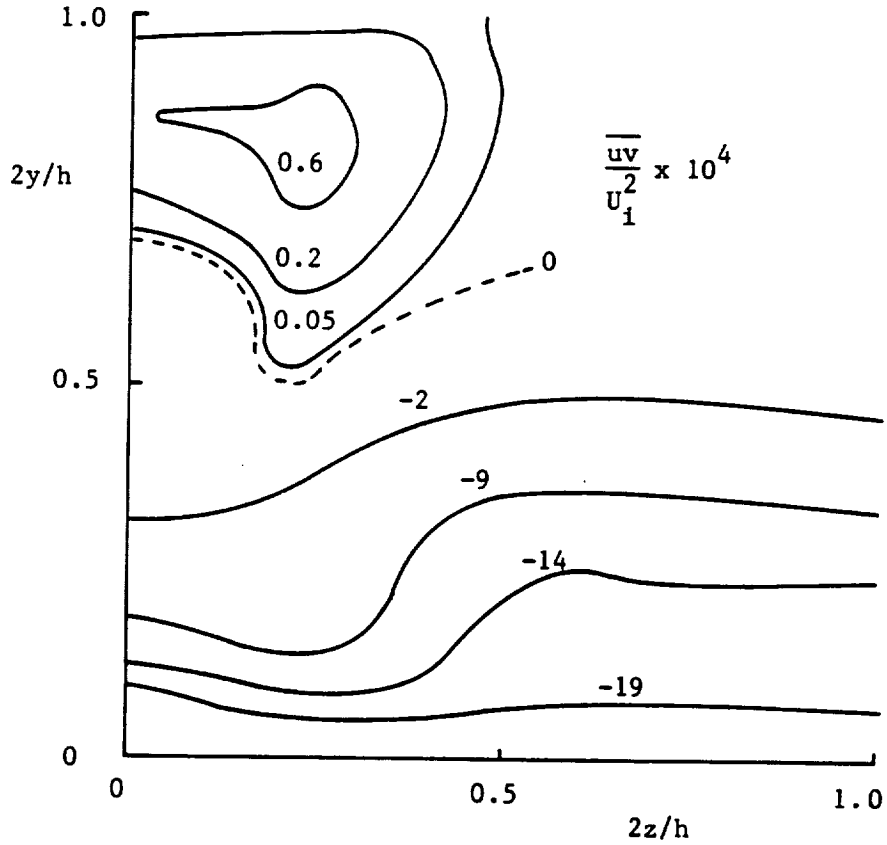
TRANSVERSE MEAN VELOCITY PATTERN AT x/c = 1.0
(VERTICAL COMPONENT BEHAVIOR)



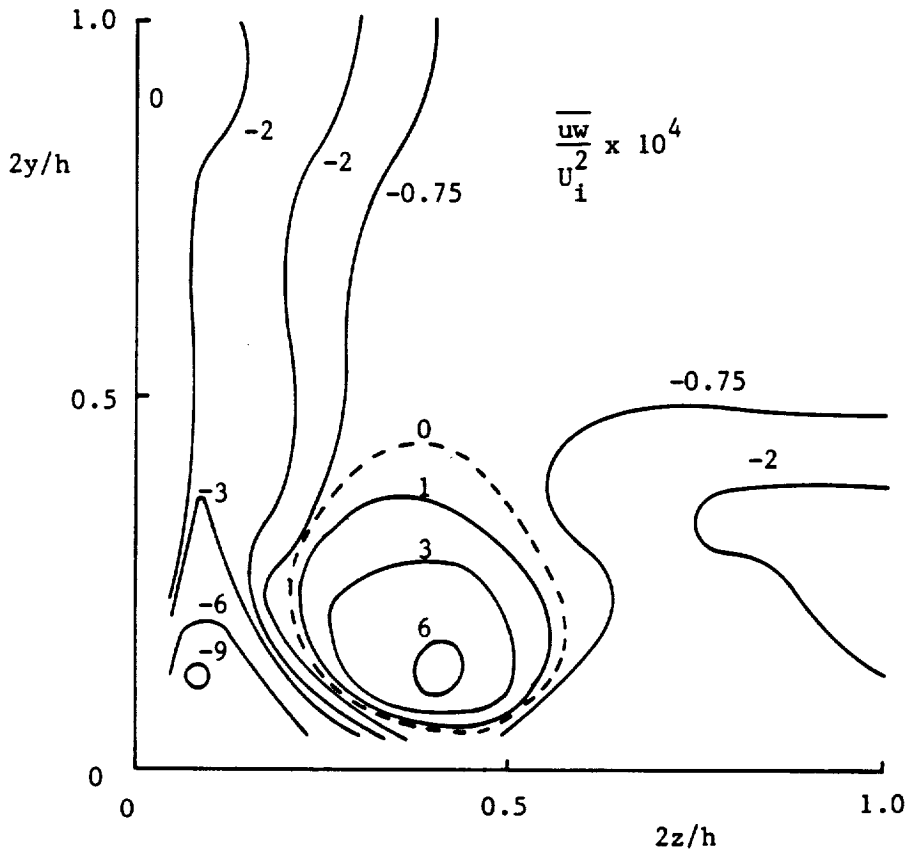
RESULTANT TRANSVERSE MEAN VELOCITY PATTERN IN WAKE REGION
(x/c = 3.3)



TURBULENCE KINETIC ENERGY CONTOURS IN WAKE REGION
(x/c = 3.3)



TURBULENCE SHEAR STRESS CONTOURS IN WAKE REGION
(x/c = 3.3)



TURBULENCE SHEAR STRESS CONTOURS IN WAKE REGION
(x/c = 3.3)

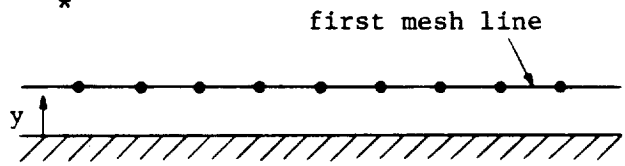
CONVENTIONAL WALL FUNCTIONS

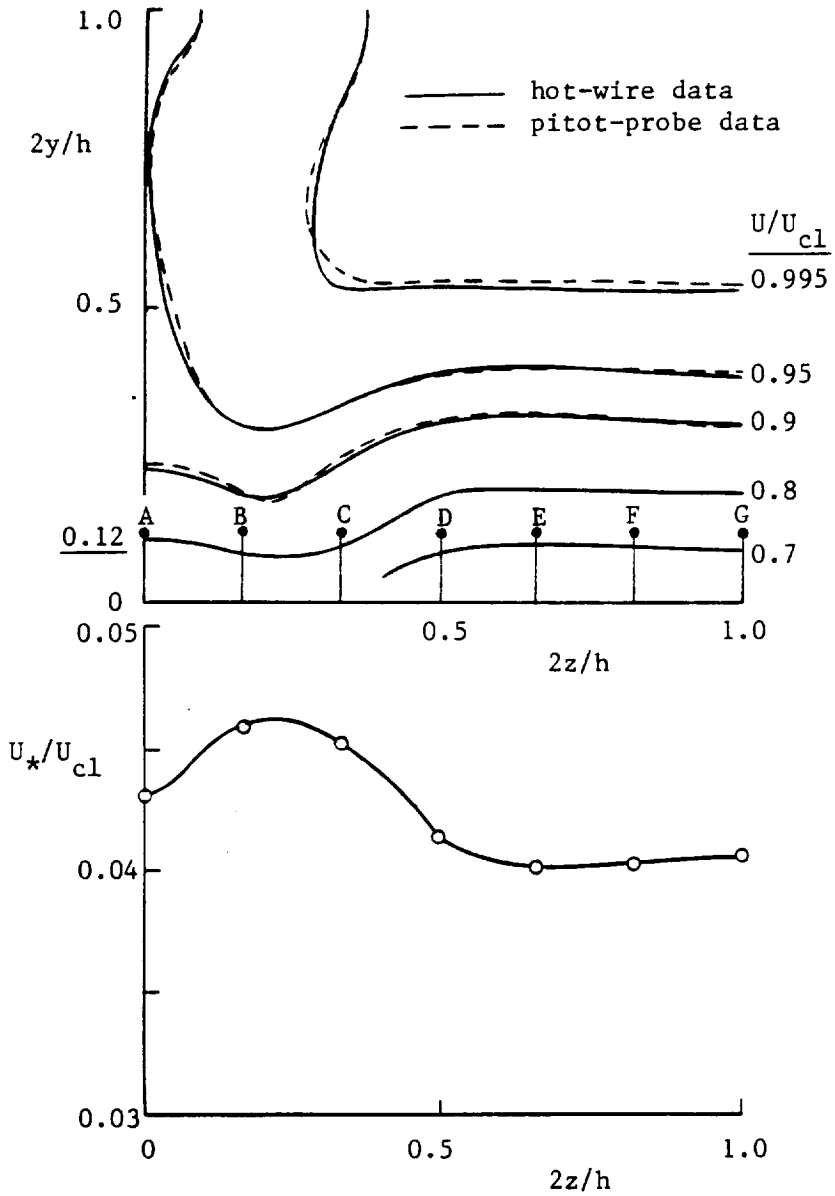
$$\frac{U}{U_*} = \frac{1}{\kappa} \ln \frac{yU_*}{\nu} + C$$

$$\frac{k}{U_*^2} = \frac{1}{c_\mu^{1/2}}$$

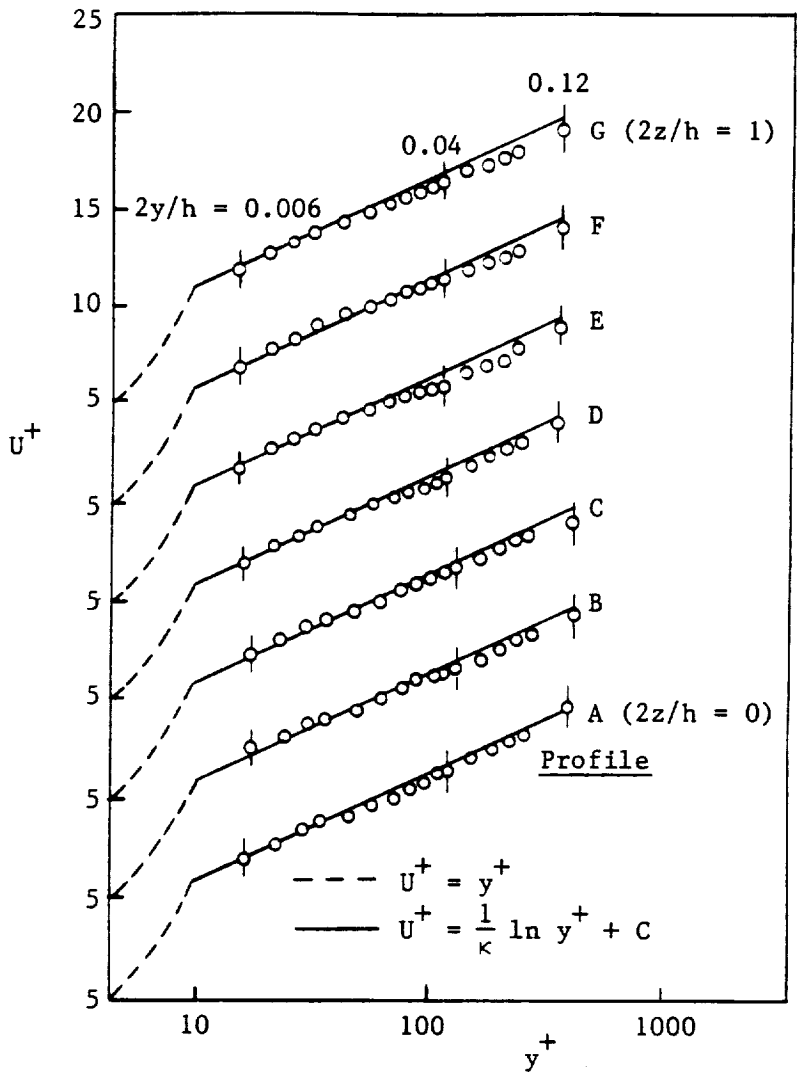
$$\frac{\varepsilon y}{U_*^3} = \frac{1}{\kappa}$$

$\kappa = 0.4$
$C = 5.1$ to 5.5
$c_\mu = 0.09$

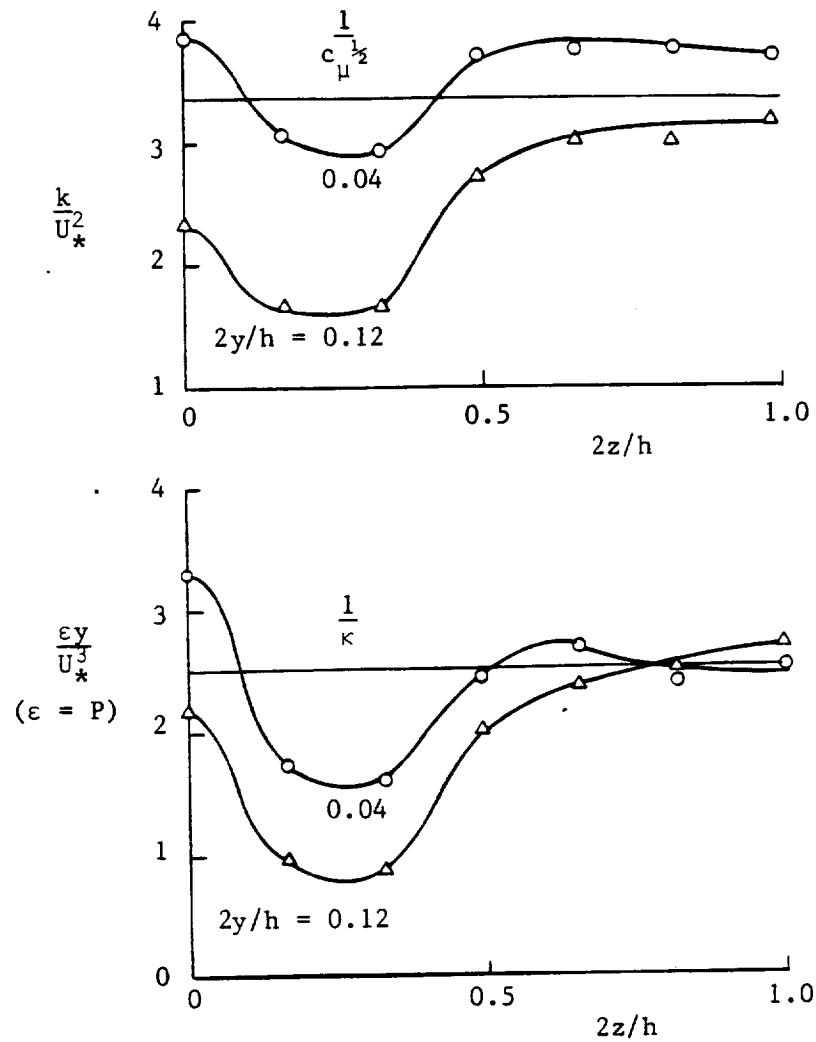




AXIAL MEAN VELOCITY CONTOURS AND SPANWISE WALL SHEAR STRESS BEHAVIOR (x/c = 3.3)



LAW-OF-THE-WALL VELOCITY PROFILES AT DIFFERENT SPANWISE LOCATIONS, $\kappa = 0.4$, $C = 5.1$ ($x/c = 3.3$)



TURBULENCE KINETIC ENERGY AND DISSIPATION RATE BEHAVIOR IN THE NEAR-WALL REGION, $\kappa = 0.4$, $c_\mu = 0.09$ (x/c = 3.3)

TURBULENT SHEAR STRESS CONSIDERATIONS

Eddy viscosity model

$$\overline{uv} = -\mu_t \frac{\partial U}{\partial y}$$

$$\overline{uw} = -\mu_t \frac{\partial U}{\partial z}$$

where

$\mu_t = (\ell_p D)^2 |\omega|$

ℓ_p = Prandtl's length scale

D = van Driest's damping factor

ω = mean vorticity

Two-equation (k-ε) model

$$\overline{uv} = -c_\mu \frac{k^2}{\varepsilon} \frac{\partial U}{\partial y}$$

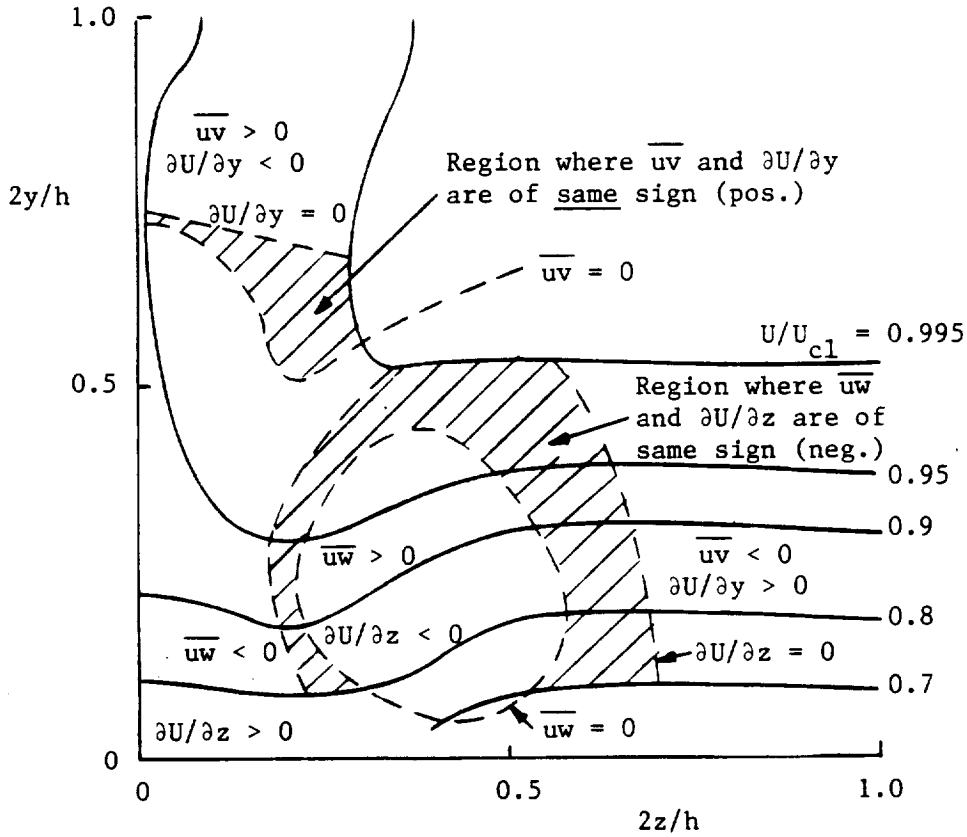
$$\overline{uw} = -c_\mu \frac{k^2}{\varepsilon} \frac{\partial U}{\partial z}$$

c_μ = prescribed coeff.

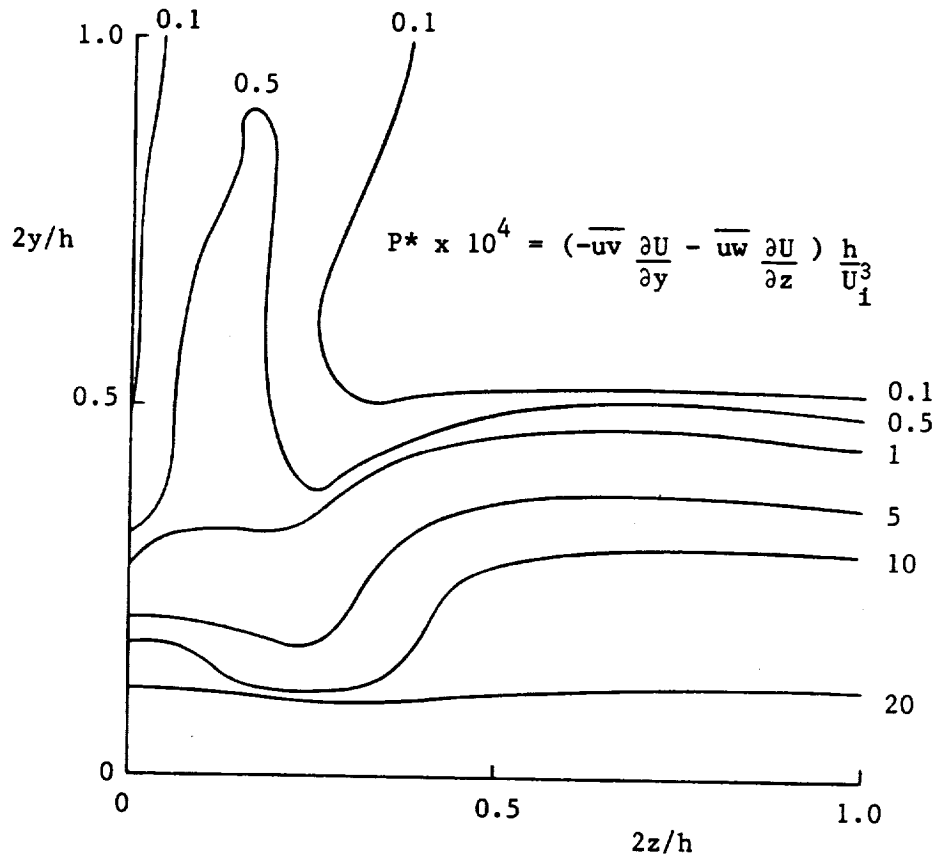
k = turbulence kinetic energy

ε = dissipation rate

Observation: Since μ_t and $c_\mu k^2/\varepsilon$ are positive in sign, $\overline{uv}$ and $\partial U/\partial y$ must be of opposite sign for compatibility. Similarly, $\overline{uw}$ and $\partial U/\partial z$ must also be of opposite sign.



REGIONS OF POSITIVE AND NEGATIVE VALUES FOR $\overline{uv}$, $\overline{uw}$, $\partial U/\partial y$, and $\partial U/\partial z$ ($x/c = 3.3$)



TURBULENCE KINETIC ENERGY PRODUCTION CONTOURS
(x/c = 3.3)

SUMMARY OF RESULTS

On the basis of the strut-endwall experiments which have been conducted to date, the following conclusions can be drawn:

1. For incompressible flow conditions, additional vortices develop downstream of the leading edge in the vicinity of the midplane ($2y/h = 1$) which co-exist with the horseshoe vortices formed by local flow separation upstream of the strut leading edge.

2. These additional vortices are driven by transverse static pressure gradients near the airfoil surface which exist when the surface boundary layer is turbulent.

3. Within the wake region downstream of the trailing edge, "pockets" of flow exist which cannot be described by conventional eddy viscosity models.

4. It may not be possible to model the near-wall behavior of k and ε accurately by means of conventional (two-dimensional) wall functions. Extended wall functions which account for spanwise variations in the local wall shear stress are likely to be more realistic.

N92-70951

REQUIREMENTS FOR CFD VALIDATION EXPERIMENTS

I. COMBINED Experiments and Computations

II. Duplication of Key Experiments and Computations

III. Clearly Defined Physics and Modeling

IV. Sensitivity Studies

V. Range

VI. Validation re REAL Conditions

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Bogdonoff, D.L.

I. COMBINED Experiments and Computations

- No computation without experiment
- Experiments designed <u>with</u> computation
  - Physics, modeling, measurements, resolution, accuracy

II. Duplication of Key Experiments and Computations

- Very few, if any, experiments are absolute
- Test conditions not <u>Totally</u> defined
- Scale
- Must verify that results are independent of specific test apparatus
- Computations - not necessarily transportable
- Different machine characteristics - sensitivity to input conditions

III. Clearly Defined Physics and Modeling

- What is key element to be examined
- Will test program provide adequate data to evaluate computation
- Is test <u>critical</u> for the model

IV. Sensitivity Studies

- Will the variables examined make any difference?
- Will the range of parameter variations provide clear trends
- Identify the parameters and variables which are most critical
- Usual grid studies - need physics - turbulence models, chemical kinetics models, etc.

V. Range

- No single point test, no matter how detailed, is adequate for validation
- Need multi dimensional matrix - defined by problem - application - explore boundaries of solutions
  M, Re, T_W/T_O, Chemical Kinetics, scale, etc.

VI. Validation re REAL Conditions

- Direct connection of experiments and computation to <u>Real</u> problem - flight - internal flow conditions
- Limitation to current W.T. facilities
- High M. flight experiments

N92-70952

A NASA/UNIVERSITY OF VIRGINIA CFD VALIDATION PROGRAM: TRANSVERSE INJECTION IN A SUPERSONIC COMBUSTOR

DR. JAMES C. MCDANIEL

DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING

UNIVERSITY OF VIRGINIA

NASA GRANTS: NAG-1-373, NAG-1-795
HYPERSONIC PROPULSION BRANCH, LRC
DR. G. B. NORTHAM, TECHNICAL MONITOR

OVERVIEW

INTRODUCTION

- AIRFRAME-INTEGRATED SCRAMJET
- BUILDING-BLOCK CFD VALIDATION OF SUPERSONIC COMBUSTOR
- TRANSVERSE INJECTION FLOWFIELD

3-D MIXING WITHOUT REACTION (NAG-1-373)

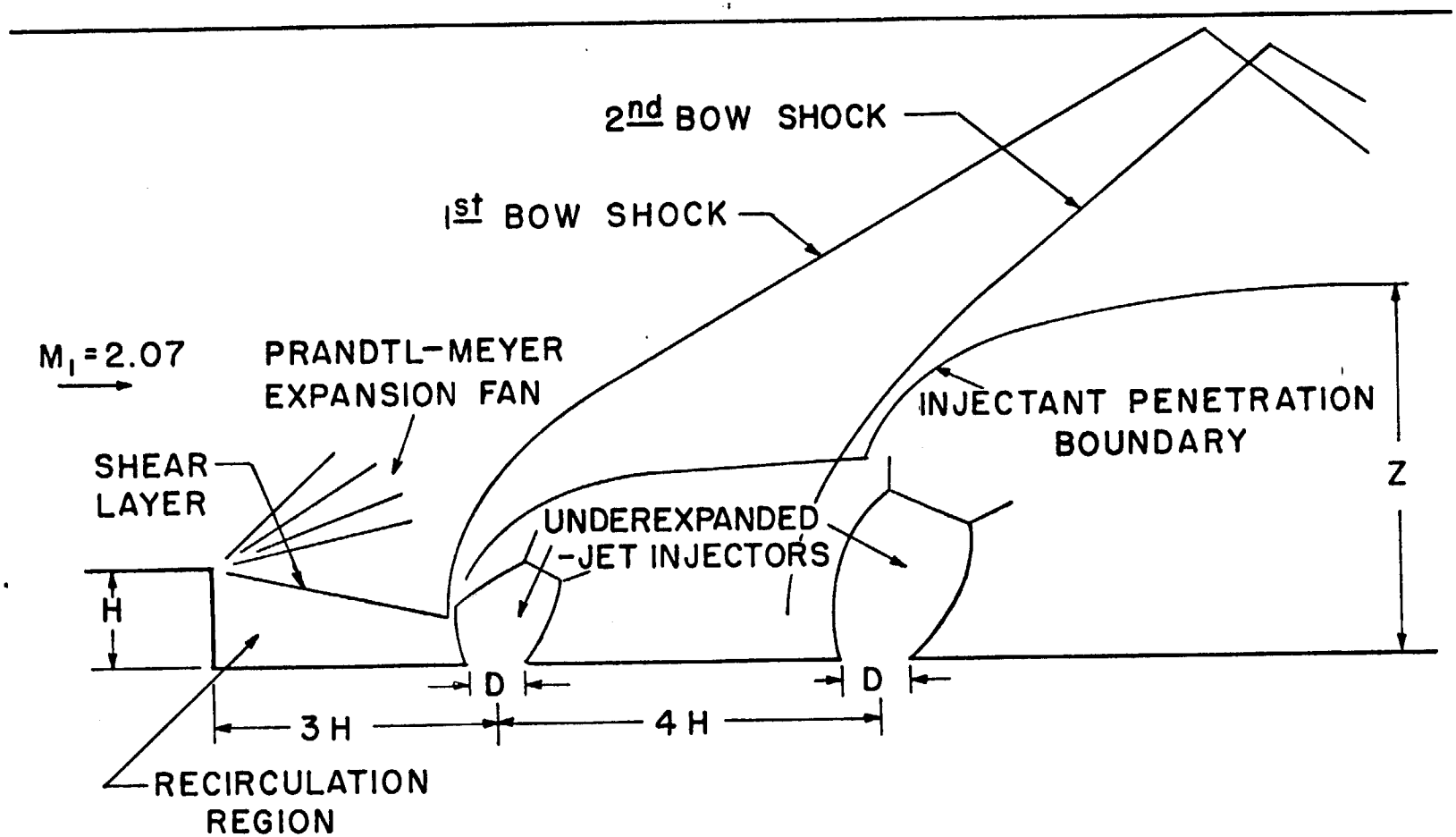
- SHADOWGRAPH/FLUORESCENCE VISUALIZATION
- QUANTITATIVE LASER-INDUCED IODINE FLUORESCENCE (LIIF) MEASUREMENTS
- CFD COMPARISONS

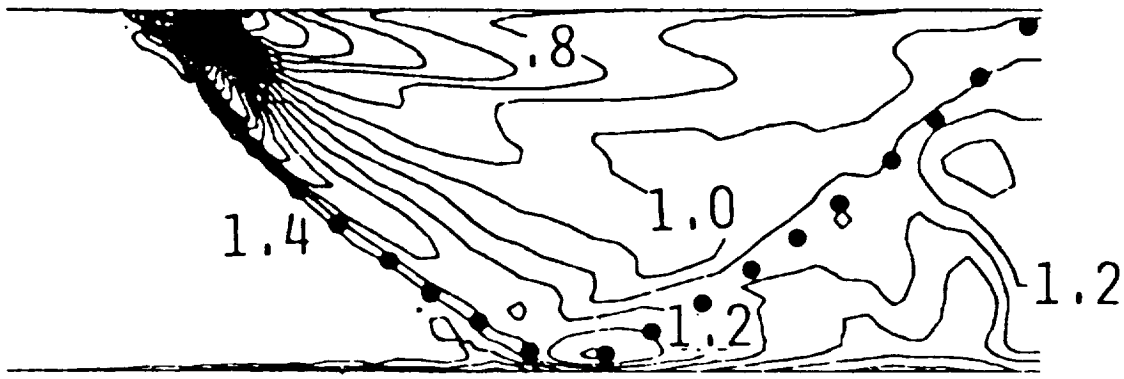
3-D MIXING AND REACTION (NAG-1-795)

- HIGH-RESOLUTION LIF TECHNIQUE: MINOR SPECIE MEASUREMENT
- FLAT-FLAME CALIBRATION EXPERIMENT
- UVA SUPERSONIC COMBUSTION FACILITY
- H_2/AIR REACTING FLOWFIELD CALCULATION

SUMMARY

STAGED, TRANSVERSE INJECTION IN A SUPERSONIC COMBUSTOR





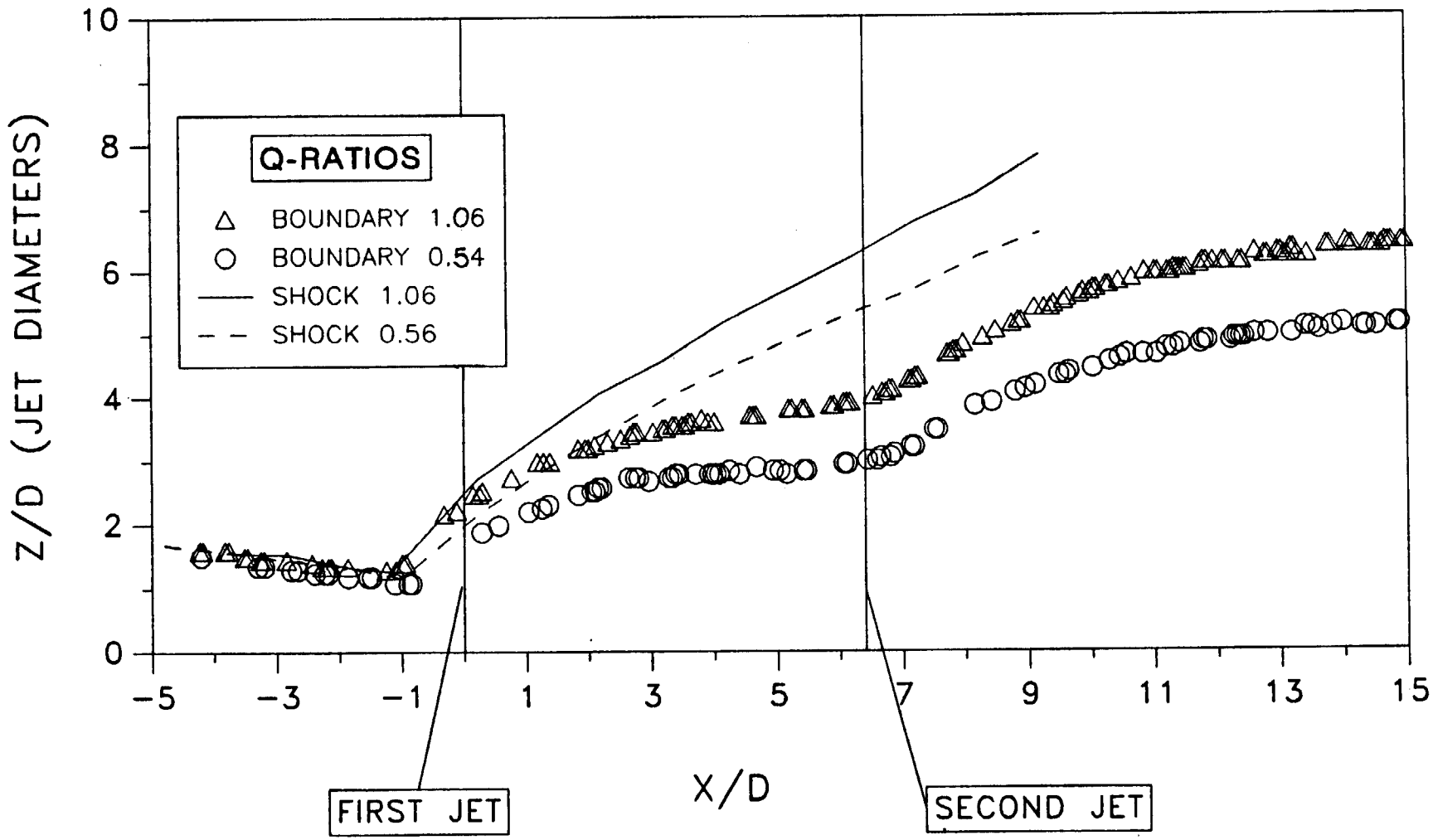
——— Computed contours (density)

● Bow shock location (shadow graph)

Bow shock location in the X-Z plane at $Y = Y_{CL}$.

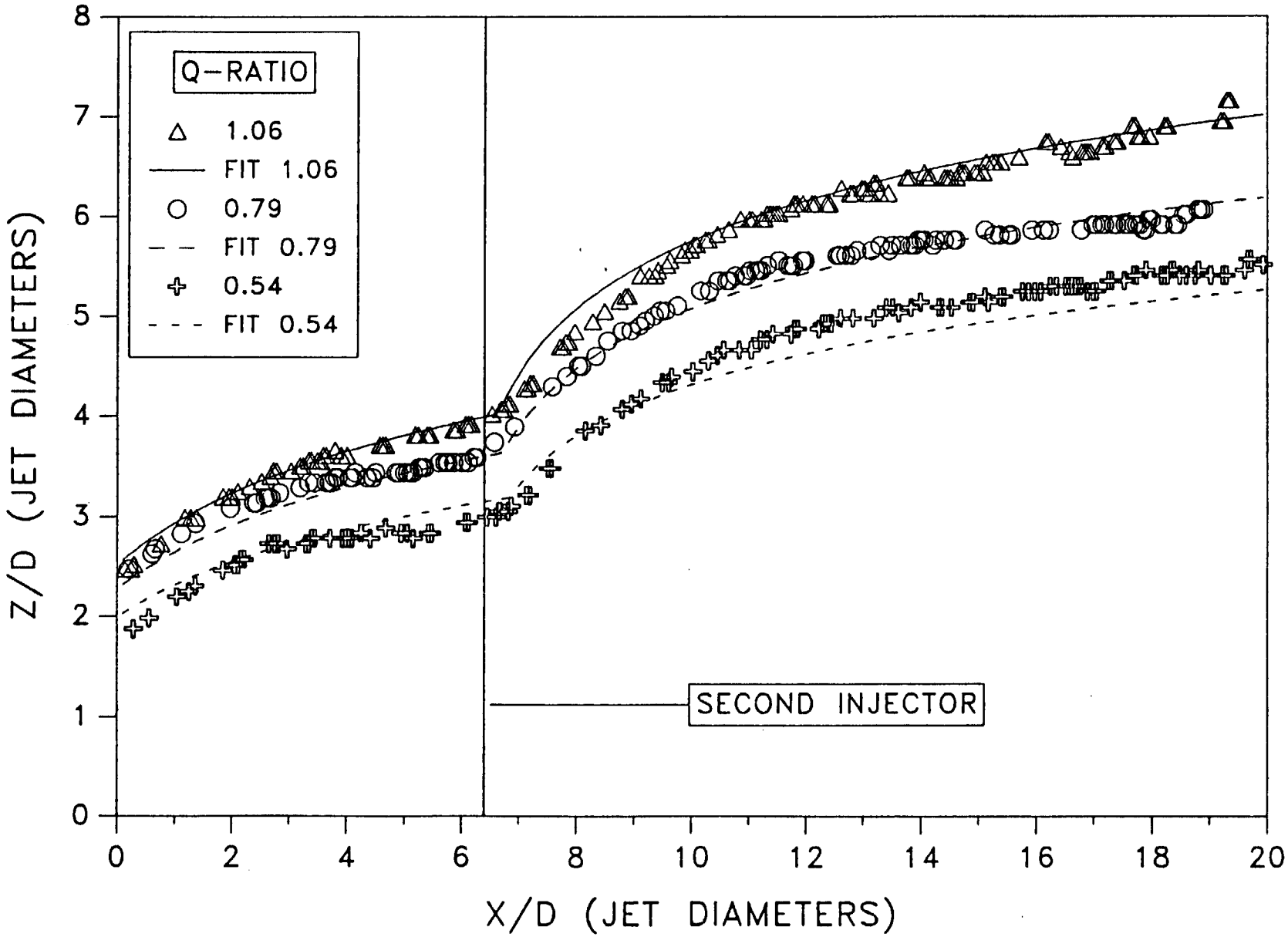
PLUME BOUNDARY & SHOCK LOCATIONS

STEPPED DUCT, STAGED INJECTION, Y/D = 0.00



INJECTANT PENETRATION BOUNDARY

STEPPED DUCT, STAGED INJECTION, Y/D = 0



PARAMETRIC EQUATION

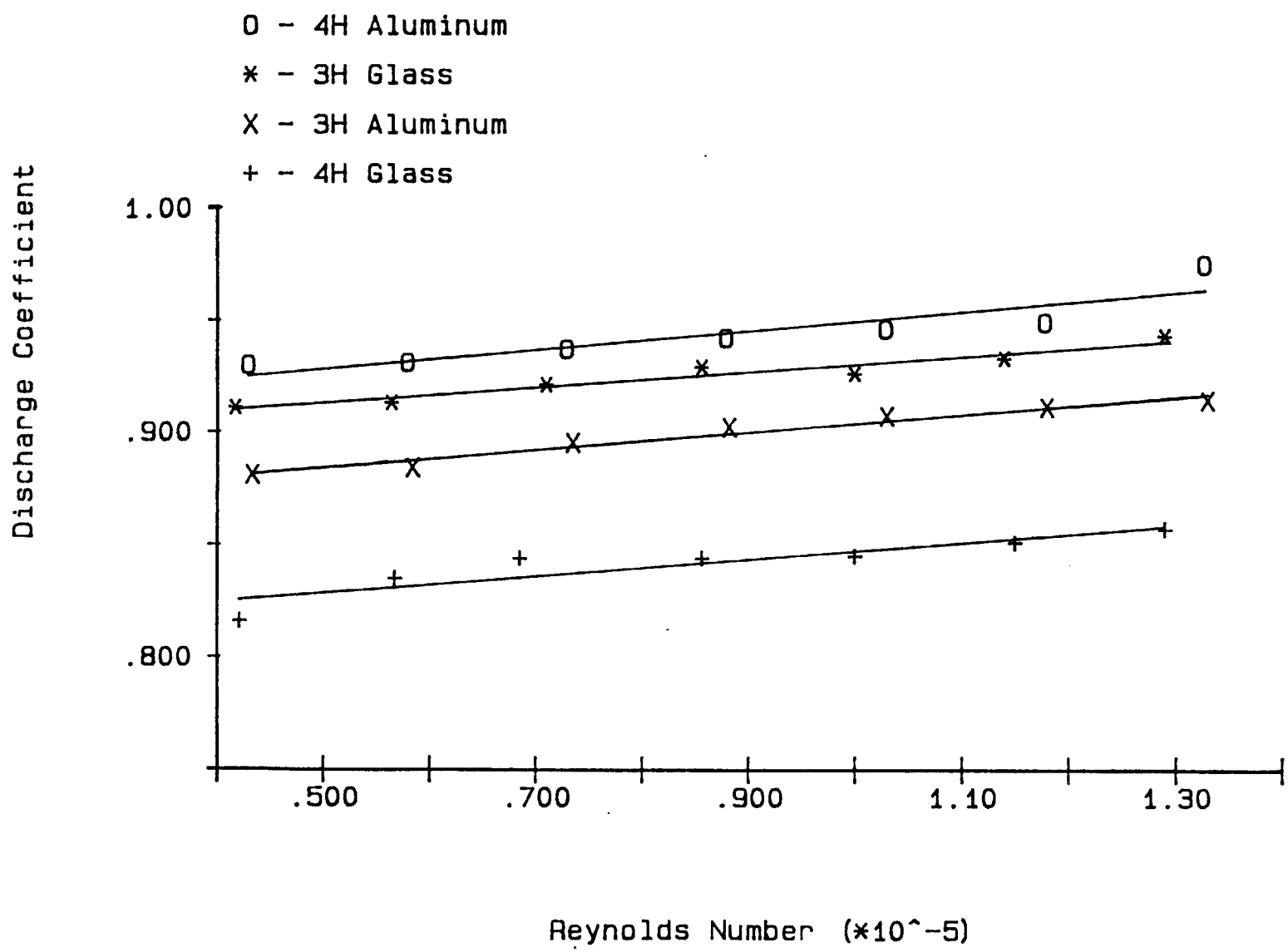
$$z/d_j = (Q_r)^{P_1} \ln(P_2(x/d_j + P_3))$$

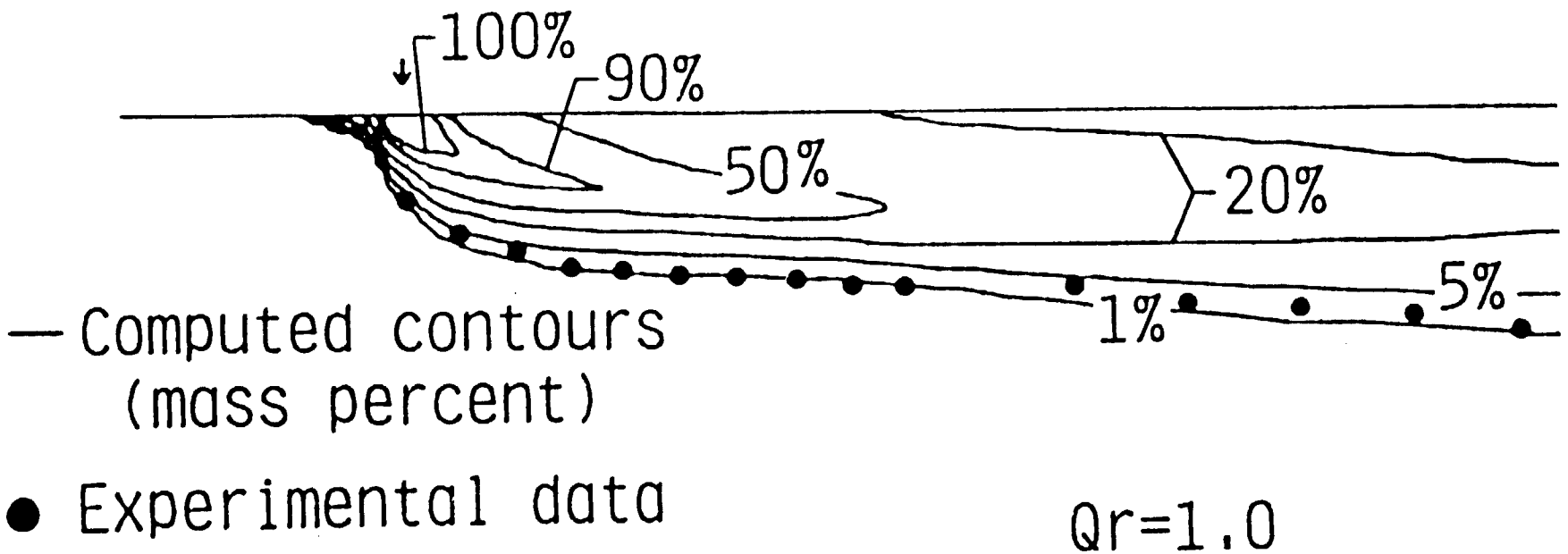
The parametric values are listed below for each configuration discussed in with the applicable mean square error, ϵ^2.

Configuration	# Cases	P_1	P_2	P_3	ϵ^2
Constant area, single jet, $y/d_j=0$	741	0.5235	2.816	6.726	0.032
Stepped duct, single injector, $y/d_j=0$	434	0.3880	4.204	3.196	0.038
Stepped duct, staged injectors;					
$y/d_j=0$					
First stage ($0 < x/d_j < 6.4$)	179	0.3516	5.973	1.968	0.013
Second stage ($x/d_j > 6.4$)	426	0.4272	66.71	-5.886	0.024
$y/d_j=1.024$					
First stage	123	0.5011	5.796	1.783	0.013
Second stage	263	0.4064	50.19	-5.752	0.022
$y/d_j=2.56$					
First stage	191	0.7611	1.453	2.861	0.031
Second stage	193	0.7603	5.997	-3.565	0.310

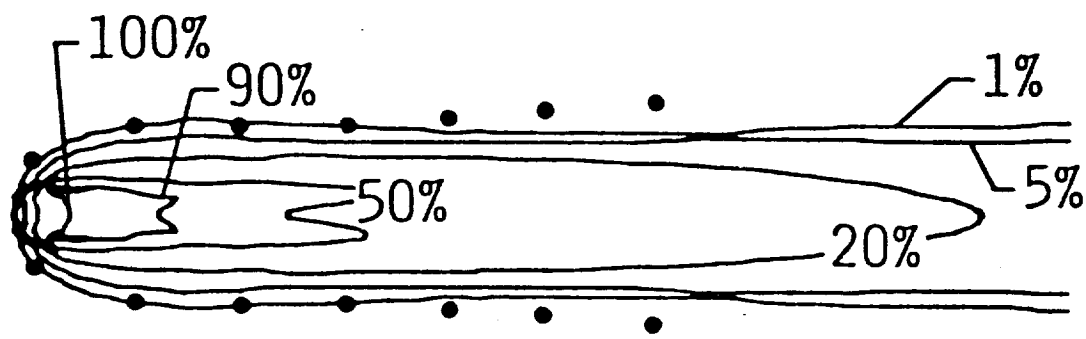
729

INJECTOR DISCHARGE COEFFICIENT





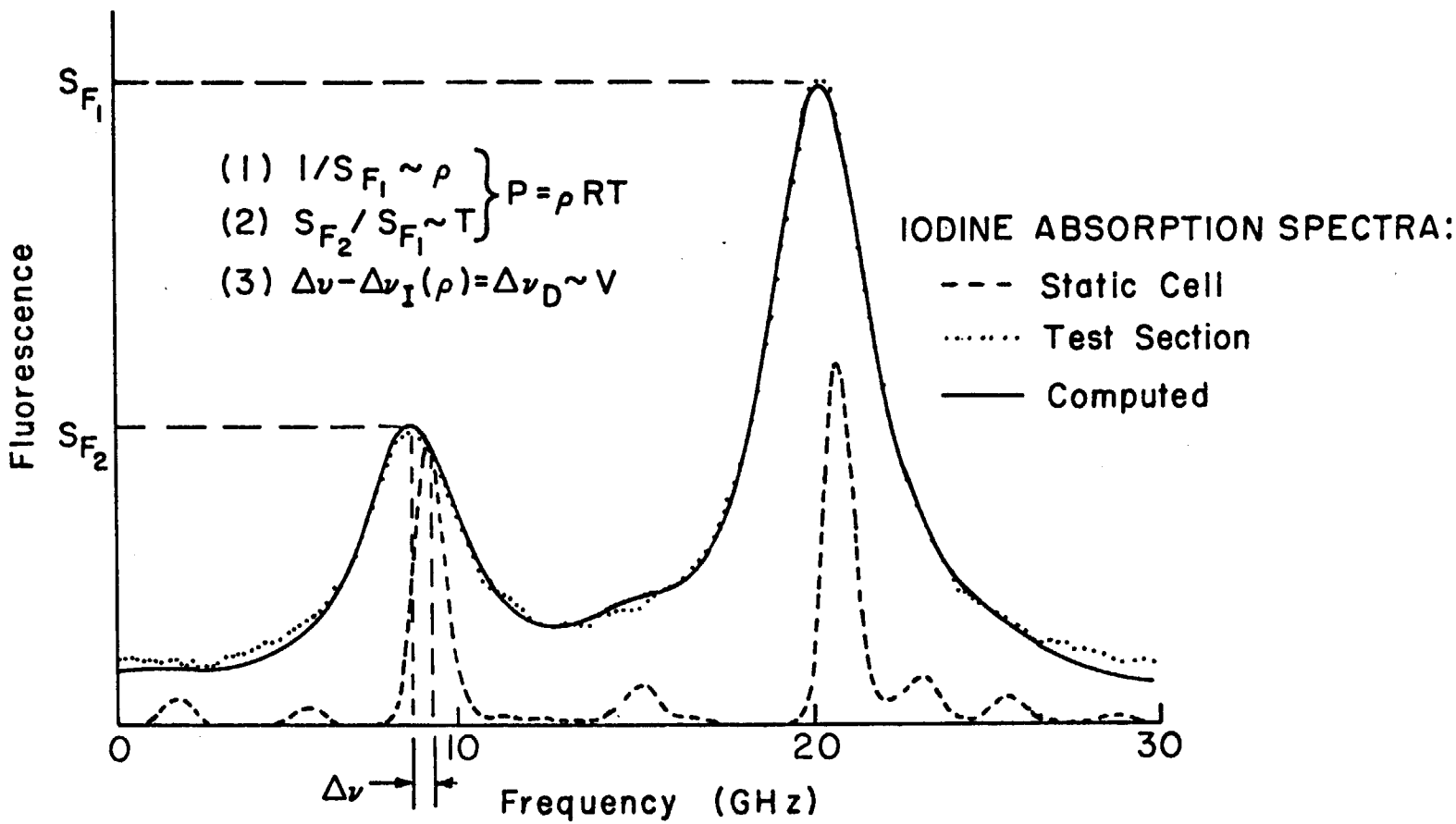
Jet penetration in the X-Z plane at $Y = Y_{CL}$.



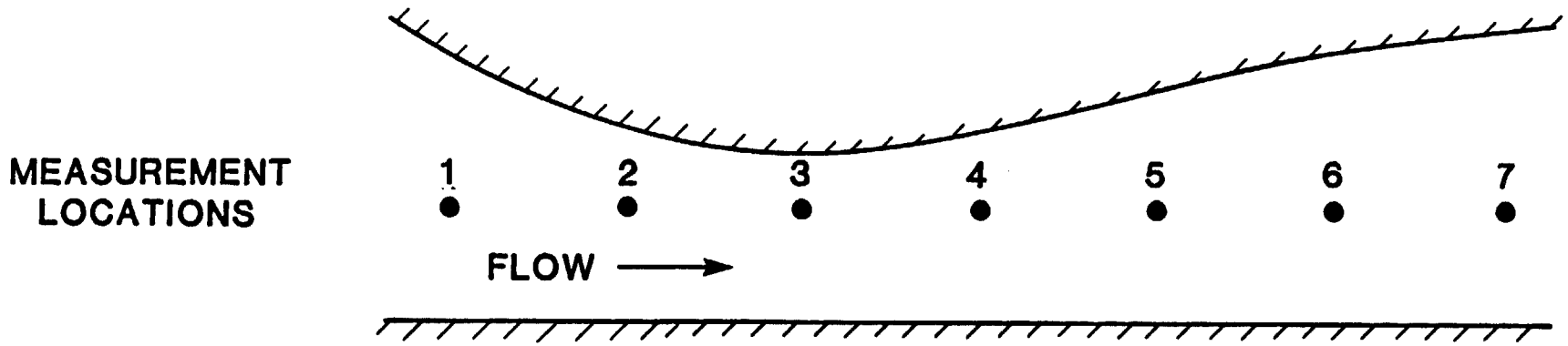
Jet spreading in the X-Y plane at $Z = Z_{TW} - d$.

LIIF OPTICAL TECHNIQUE

SPECTRAL LINECENTER RELATIONSHIP TO GASDYNAMIC VARIABLES

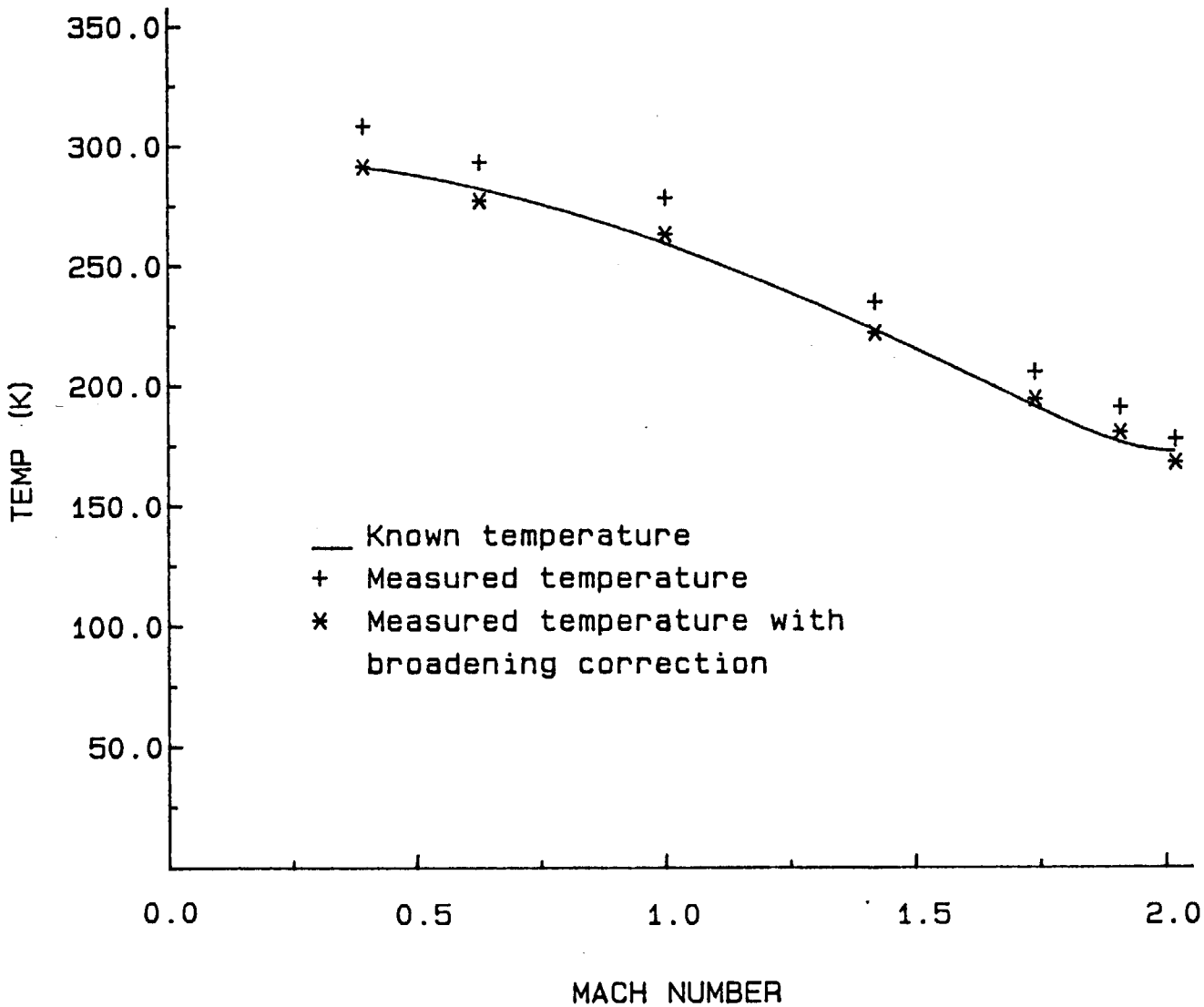


Laval Nozzle Calibration



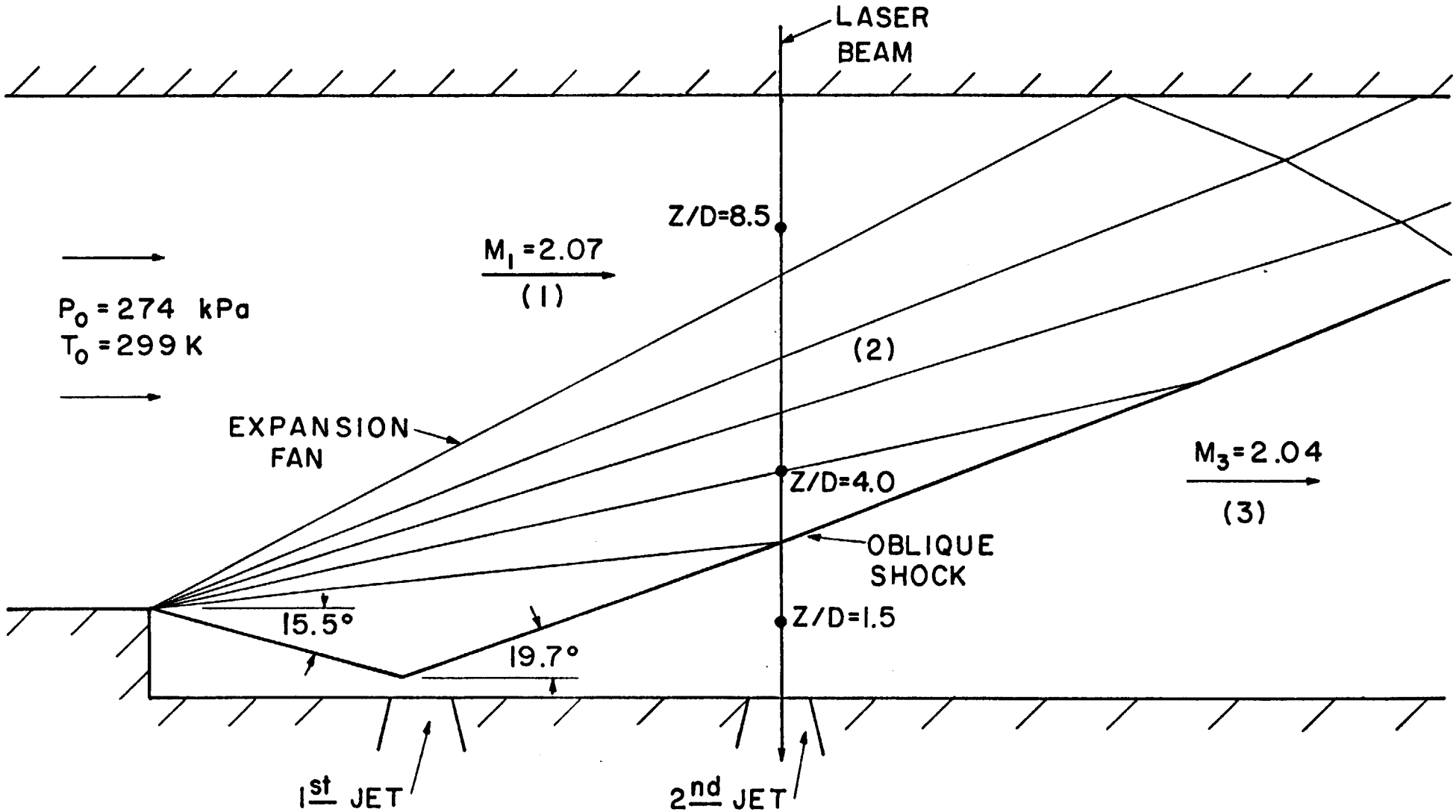
LOCATION NUMBER	1	2	3	4	5	6	7
MACH NUMBER	0.39	0.63	1.0	1.42	1.74	1.91	2.02
T, °K (T_0 = 300°K)	291	278	250	214	187	173	165
P, ATM (P_0 = 2.7 ATM)	2.43	2.07	1.43	0.82	0.51	0.40	0.33

Temperature Calibration In Laval Nozzle



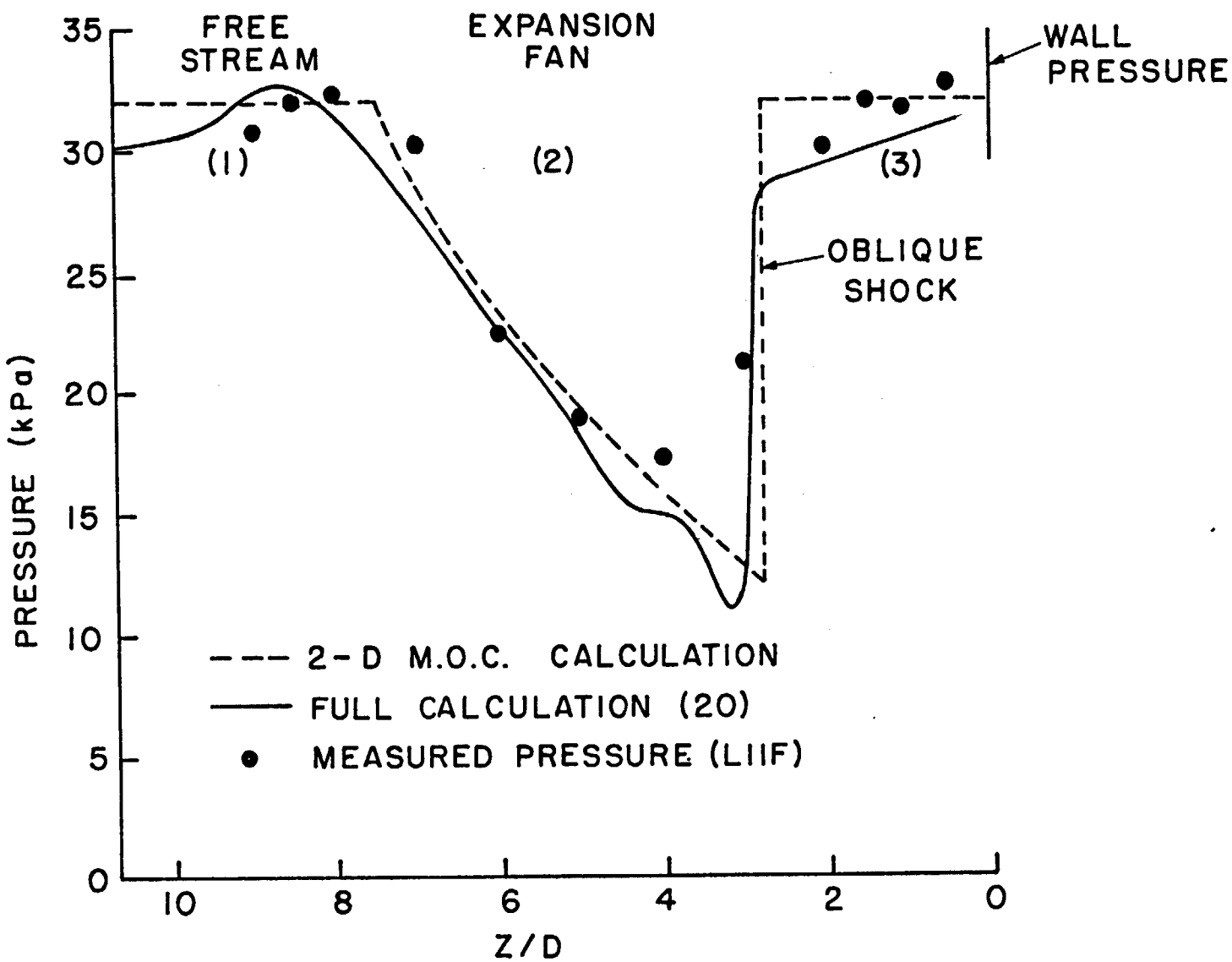
FLOW OVER REARWARD-FACING STEP: NO INJECTION

2-D, METHOD-OF-CHARACTERISTICS SOLUTION

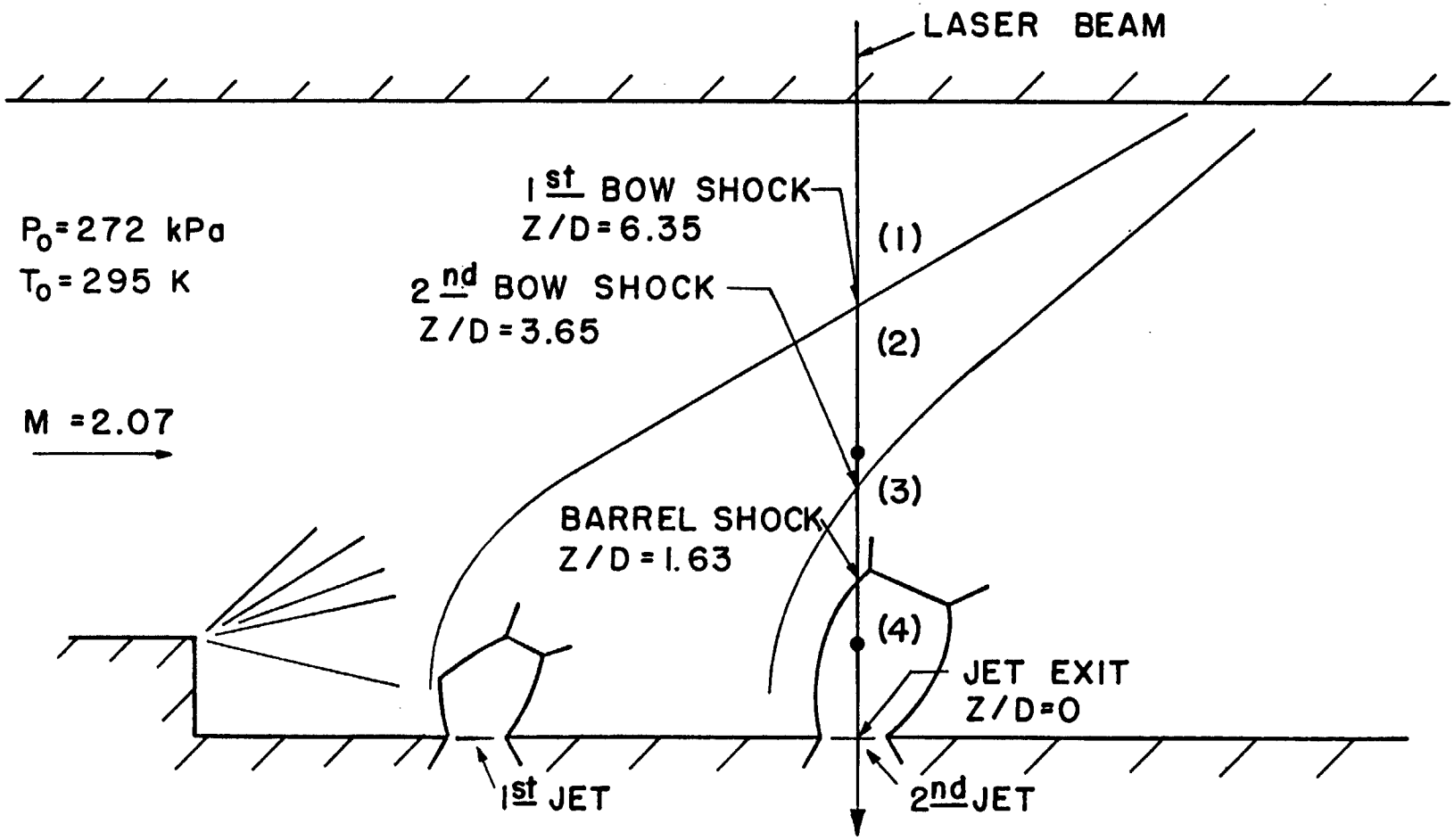


FLOW OVER REARWARD-FACING STEP WITHOUT INJECTION:

MEASURED AND CALCULATED PRESSURE DISTRIBUTIONS

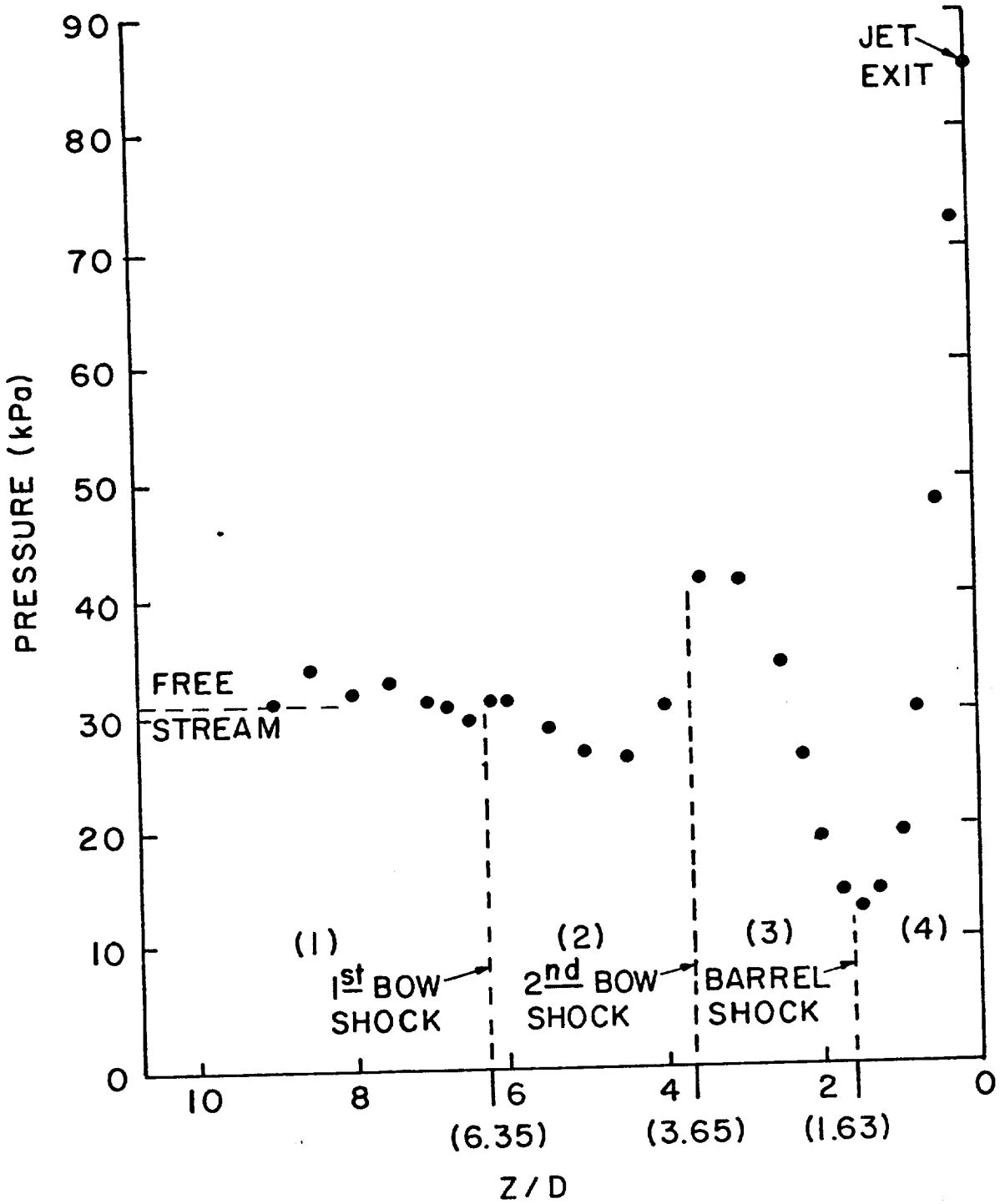


MEASUREMENTS ALONG 2nd JET CENTERLINE: $\bar{q}$=1.06



PRESSURE PROFILE: $\bar{q}$ = 1.06

2nd JET CENTERLINE



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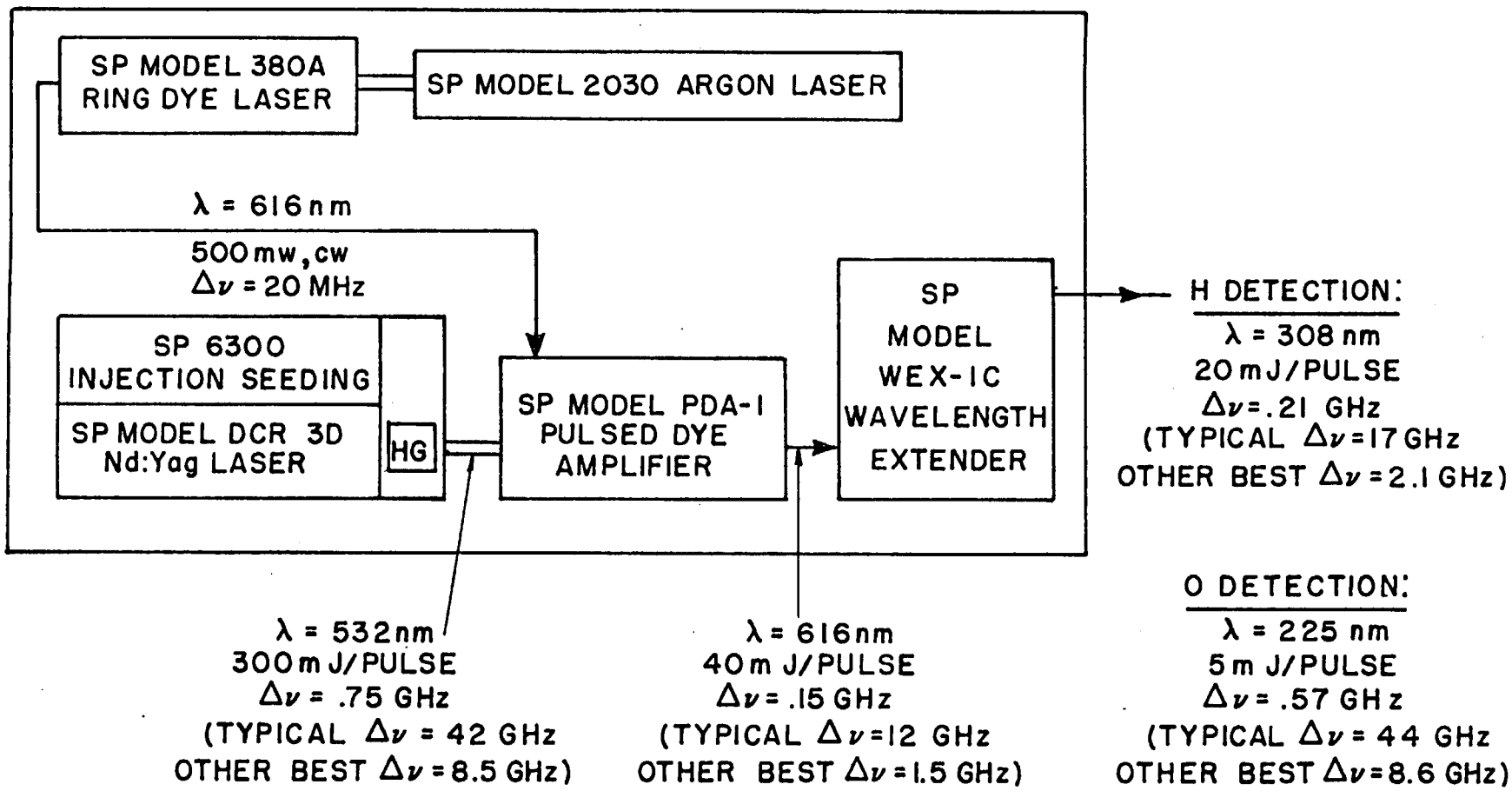
LASER EXCITATION/LIF DETECTION OF IMPORTANT RADICAL SPECIES

	SPECIES	EXITATION	DETECTION
1.	H	308nm, THREE-PHOTON ABSORPTION	656nm
		292nm, THREE-PHOTON ABSORPTION	486nm
2.	O	225nm, TWO-PHOTON ABSORPTION	778 or 845nm
3.	OH	281nm, SINGLE-PHOTON ABSORPTION	~312nm
4.	NO	225nm, SINGLE-PHOTON ABSORPTION	~250nm
		450nm, TWO-PHOTON ABSORPTION	~250nm
5.	NO_2	450nm, SINGLE-PHOTON ABSORPTION	~580nm
6.	NH	305nm, SINGLE-PHOTON ABSORPTION	~334nm

UVA TUNABLE NARROW-LINEWIDTH, NEAR-UV LASER SOURCE

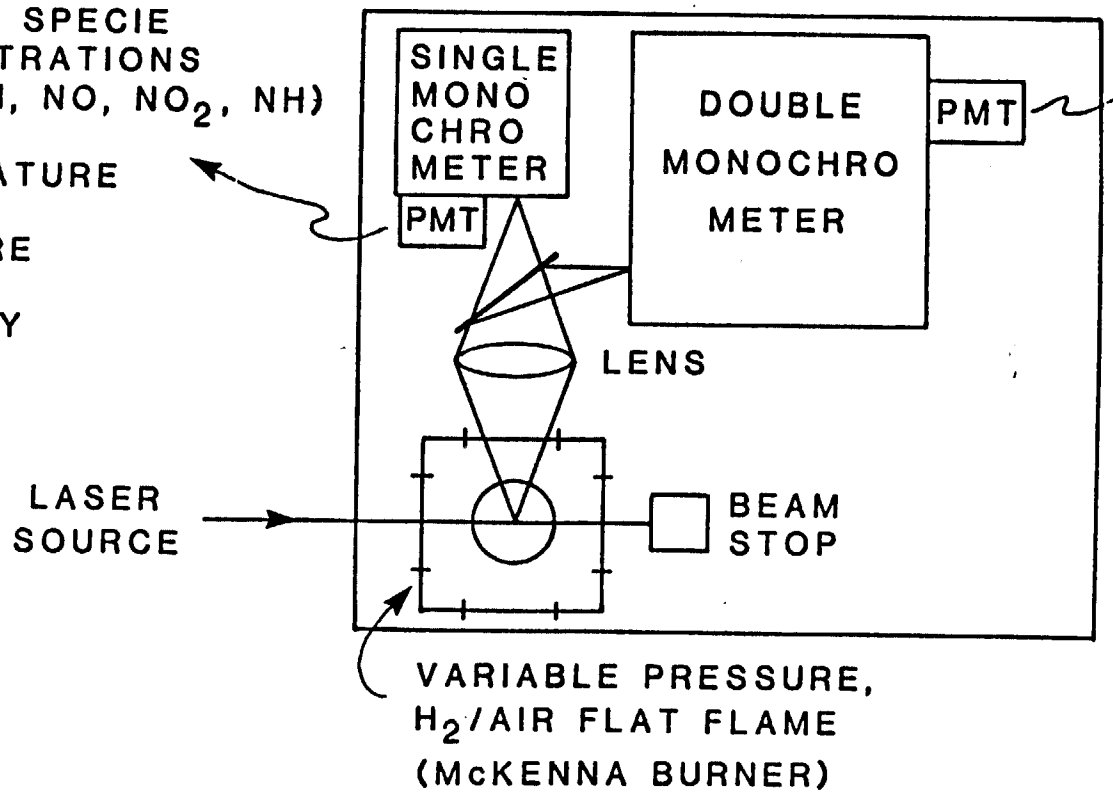


LASER-INDUCED FLUORESCENCE / RAMAN SCATTERING:

FLAT-FLAME CALIBRATION EXPERIMENT

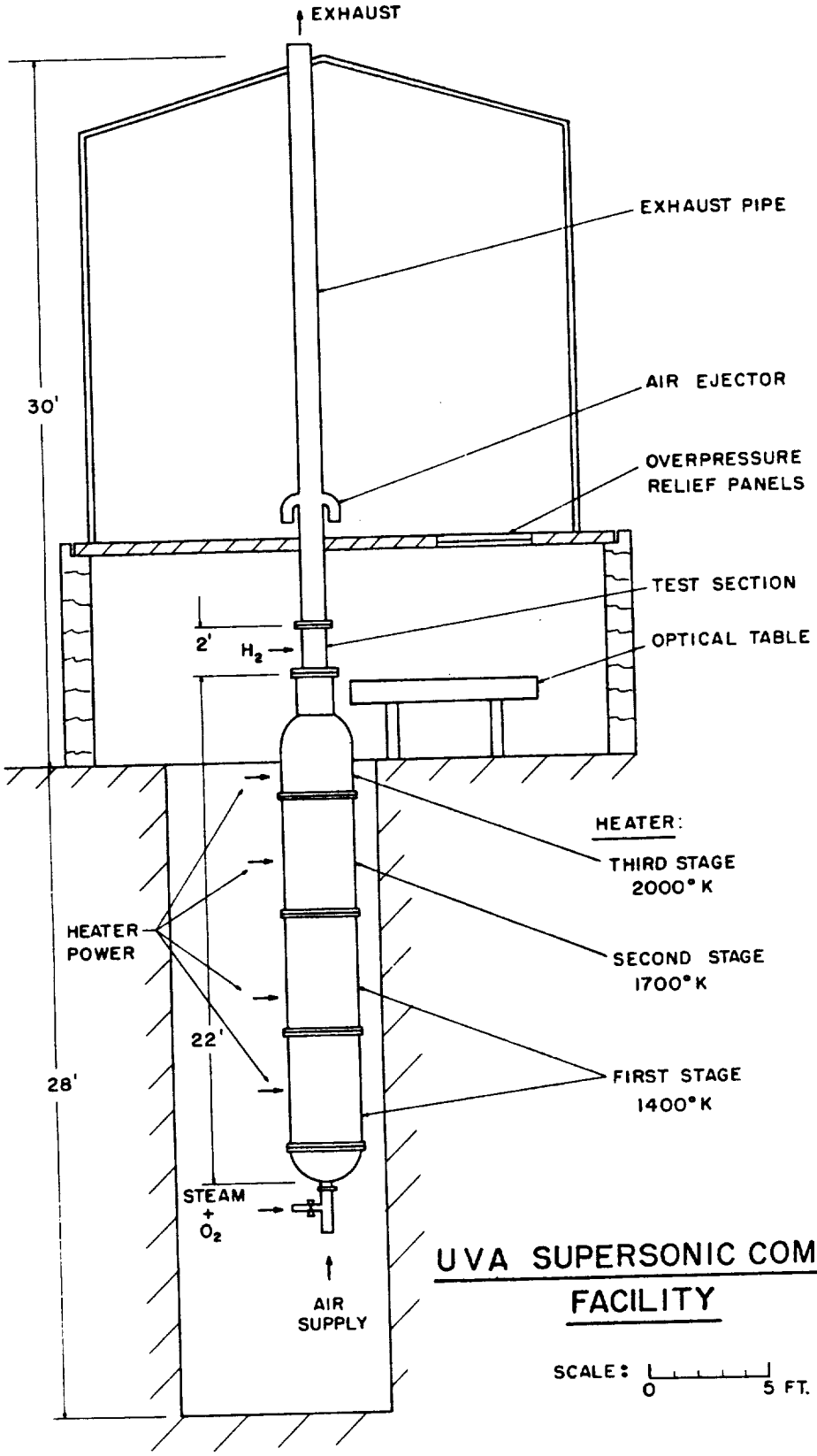
LIF

1. RADICAL SPECIE CONCENTRATIONS (H, O, OH, NO, NO_2, NH)
2. TEMPERATURE
3. PRESSURE
4. VELOCITY



SRS

1. MAJOR SPECIE CONCENTRATIONS (N_2, O_2, H_2, H_2O, STOKES VIBRATIONAL BANDS)
2. TEMPERATURE (N_2 STOKES/ ANTI-STOKES)



UVA SUPERSONIC COMBUSTION FACILITY

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SUMMARY

- PROGRAM OBJECTIVE: BUILDING-BLOCK CFD VALIDATION OF SUPERSONIC COMBUSTOR, WITHOUT AND WITH REACTION

- 3-D MIXING WITHOUT REACTION MEASURED USING SHADOWGRAPH AND FLUORESCENCE VISUALIZATION PLUS QUANTITATIVE LIIF. MEASUREMENTS AND CFD VALIDATION IN PROGRESS.

- 3-D MIXING AND REACTION TO BE MEASURED USING A UNIQUE, COMBINED LIF/RAMAN TECHNIQUE IN A HIGH-TEMPERATURE, CLEAN-AIR SUPERSONIC COMBUSTION FACILITY UNDER CONSTRUCTION AT UVA. FLAT-FLAME EXPERIMENT IN PROGRESS, COMBUSTION FACILITY OPERATIONAL NEXT SUMMER, GLOBAL FINITE-RATE CFD SOLUTION AVAILABLE FOR VALIDATION.

REMARKS ON CFD VALIDATION

A BOEING COMMERCIAL AIRPLANE COMPANY PERSPECTIVE

Paul E. Rubbert

N92-70953

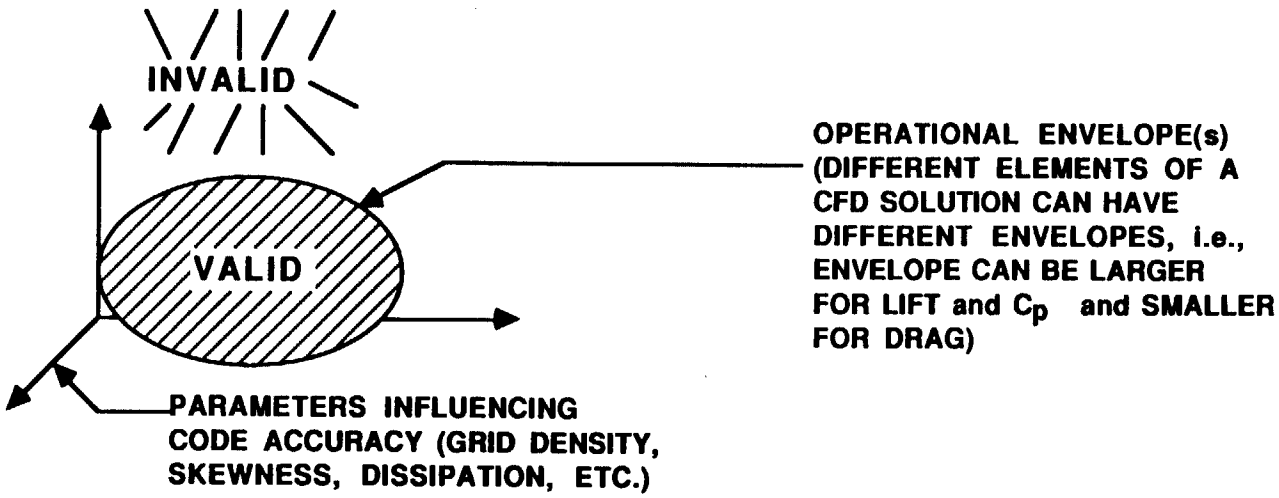
OUTLINE

- BASIC CONCEPTS IN CFD VALIDATON
- OBSERVATIONS CONCERNING THE EARLY YEARS OF A NEW CODE.
- WHAT SHOULD BE DONE TO ACCELERATE THE GROWTH IN USEFULNESS OF NEW CODES
- FLOW CATEGORIES RELEVANT TO TRANSPORT AIRCRAFT

BASIC CONCEPTS IN CFD VALIDATION

- VALIDATED CODE
- VALIDATED USER
- CALIBRATED CODE

WHAT CONSTITUTES A VALIDATED CODE

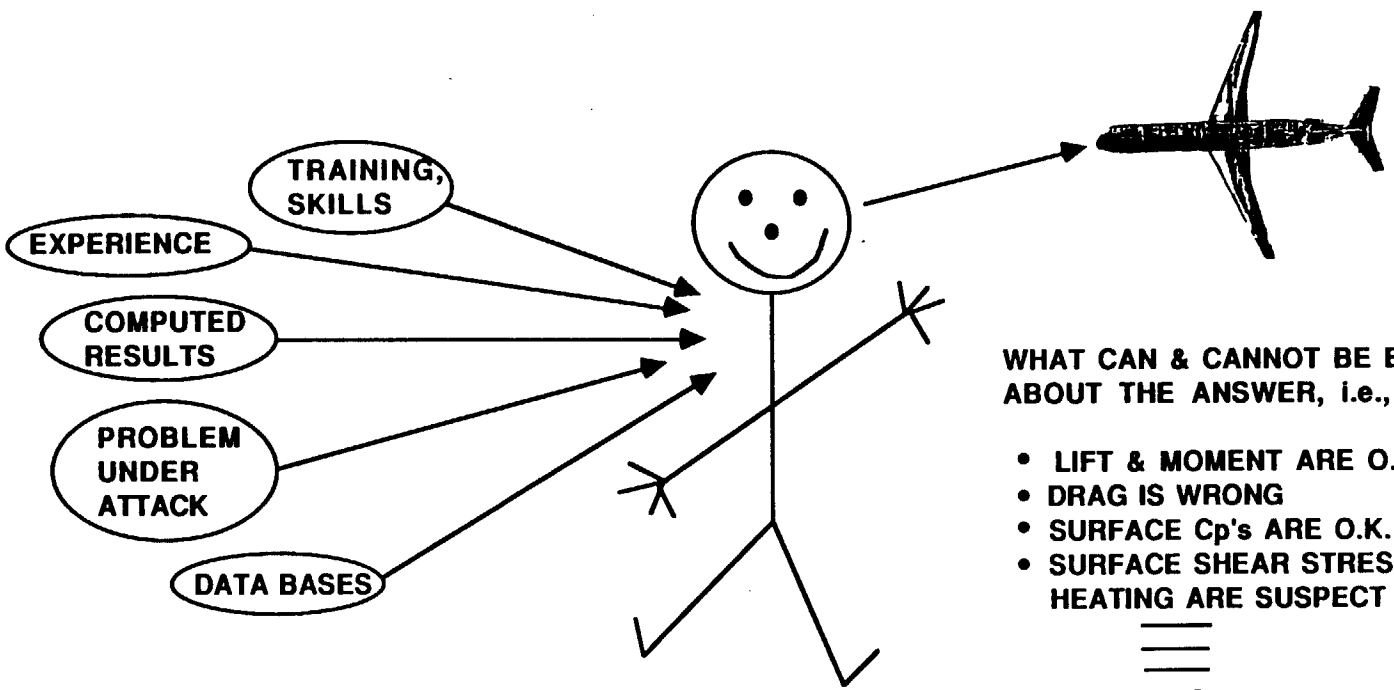


A VALIDATED CODE IS ONE FOR WHICH:

- THE PARAMETERS AFFECTING ACCURACY ARE KNOWN.
- THE OPERATIONAL ENVELOPE(s) OF THESE PARAMETERS ARE KNOWN, WITHIN WHICH THE NUMERICAL SOLUTION GIVEN BY THE CODE WILL ACCURATELY REFLECT THE PHYSICS OF THE UNDERLYING DIFFERENTIAL EQUATIONS THAT ARE BUILT INTO THE CODE.

WHAT CONSTITUTES A VALIDATED USER

THE PRIMARY MISSION OF THE VALIDATED USER IS TO JUDGE WHETHER THE PHYSICS CONTAINED WITHIN A CODE AND ITS COMPUTATIONAL RESULTS REFLECT THE TRUE PHYSICS OF THE PROBLEM OF INTEREST



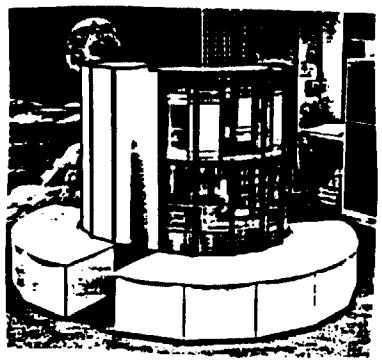
WHAT CAN & CANNOT BE BELIEVED ABOUT THE ANSWER, i.e.,

- LIFT & MOMENT ARE O.K.
- DRAG IS WRONG
- SURFACE Cp's ARE O.K.
- SURFACE SHEAR STRESS & HEATING ARE SUSPECT

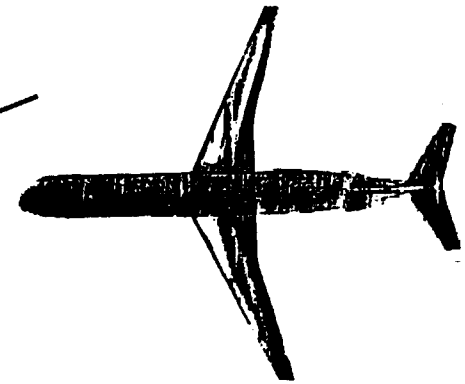
ETC.

WHAT IS A CALIBRATED CODE

COMPUTATION



EXPERIMENT

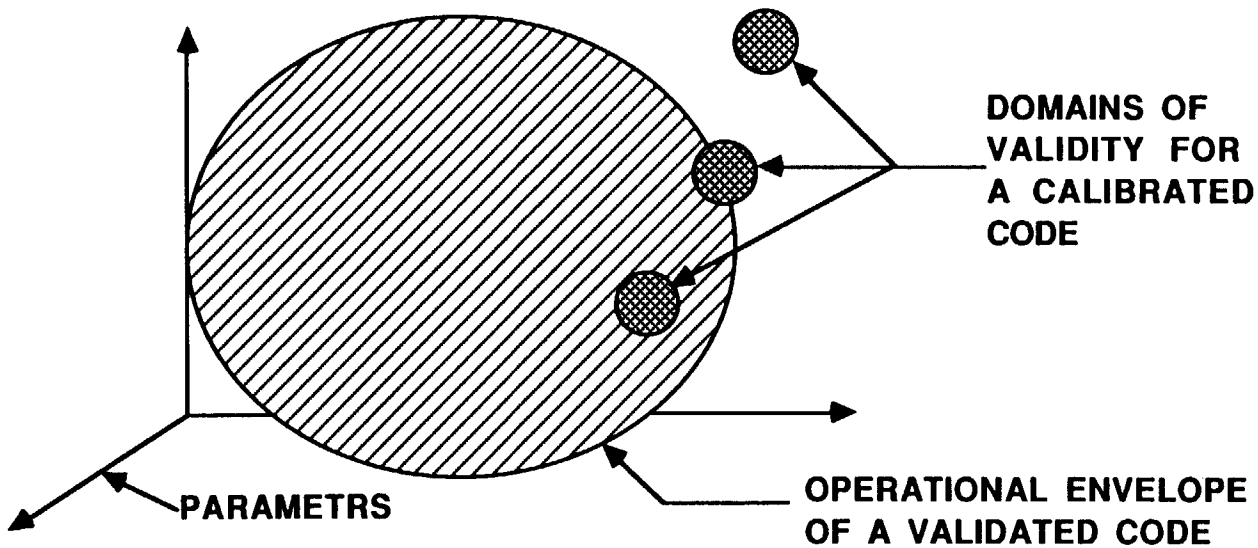


COMPUTATIONAL PARAMETERS ADJUSTED TO GIVE AGREEMENT WITH EXPERIMENT

A CALIBRATED CODE IS:

- A CODE THAT IS OPERATED OUTSIDE OF ITS KNOWN OPERATIONAL ENVELOPE AND WITH ITS PARAMETERS ADJUSTED TO GIVE AGREEMENT WITH EXPERIMENT.
- USEFUL FOR FLOWS WHICH ARE CLOSE TO THE CALIBATING EXPERIMENT.
- GENERALLY REQUIRES CALIBRATING EXPERIMENTS TO BE PERFORMED ON A CASE-BY-CASE BASIS.

RELATIONSHIP BETWEEN CALIBRATED AND VALIDATED



OBSERVATIONS CONCERNING THE EARLY YEARS OF A NEW CODE

- A NEW CFD CODE FREQUENTLY "STRAINS THE GASKETS" OF ITS HOST COMPUTER, AND IS NOT USER FRIENDLY.

- MAY BE PHYSICALLY IMPOSSIBLE TO RUN THE PROBLEM SIZES AND VOLUMES NEEDED TO ACHIEVE VALIDATION.

- THE USER COMMUNITY & NOT THE CODE DEVELOPER DETERMINES THE ULTIMATE ROLE OF A CODE IN ENGINEERING DESIGN. AN EARLY FOCUS ON VALIDATION COULD MISS THE MARK.

- EARLY USAGE TYPICALLY INVOLVES <u>CALIBRATION</u> FOR SELECTED PROBLEMS OF INTEREST ON A CASE-BY-CASE BASIS.

- A CODE THAT BECOMES VALIDATED HAS TYPICALLY UNDERGONE MANY CHANGES AND IMPROVEMENTS DURING THE CALIBRATION & VALIDATION PROCESS. DON'T UNDERTAKE VALIDATION WITHOUT PLANNING FOR CODE MODIFICATIONS and ENHANCEMENTS.

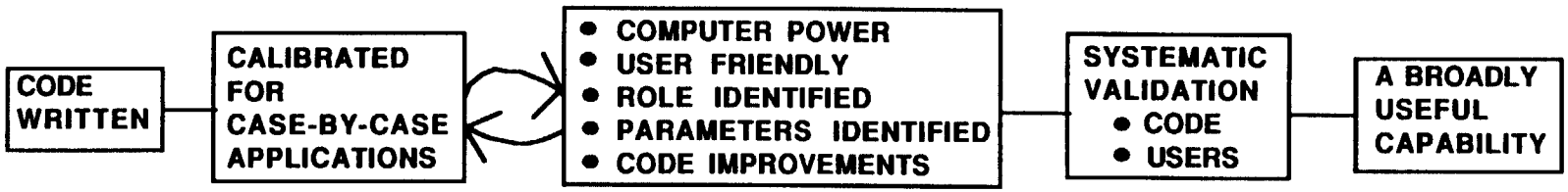
OBSERVATIONS ~ CONTINUED

CODES BECOME AMENABLE TO VALIDATION AFTER THE FOLLOWING EVENTS:

- COMPUTER POWER HAS GROWN TO ALLOW LARGE PROBLEM SIZES AND DATUM RUNS.
- USER FRIENDLINESS PERMITS LARGE NUMBER OF RUNS.
- INITIAL USAGE EXPERIENCE HAS IDENTIFIED THE ROLE OF THE CODE IN SCIENCE AND ENGINEERING.
- THE PARAMETERS FORMING THE FOUNDATION FOR VALIDATION HAVE BEEN IDENTIFIED (IT IS NOT UNUSUAL TO UNCOVER NEW PHYSICS THAT WAS NOT ANTICIPATED).
- MANY CODE IMPROVEMENTS HAVE BEEN INCORPORATED IN RESPONSE TO INITIAL ATTEMPTS AT CALIBRATION & CALIBRATED USAGE.

WHAT SHOULD BE DONE TO ACCELERATE THE GROWTH IN USEFULNESS OF NEW CODES

1. RECOGNIZE THE NATURAL SEQUENCE OF EVENTS.



2. RECOGNIZE THE NEED ALSO FOR CALIBRATED USERS.

3. DO THOSE THINGS THAT CAN ACCELERATE EVENTS.

RECOMMENDED STRATEGY

- DEMAND SYSTEMATIC INTERNAL CONSISTENCY & CONVERGENCE CHECKS OF NEW CODES. THE AIM IS TO <u>ESTABLISH THAT THE CODE GIVES A SOLUTION THAT APPROXIMATES THE SOLUTION TO THE UNDERLYING DIFFERENTIAL EQUATION(s) WITHIN A KNOWN AND PREDICTABLE LEVEL OF ACCURACY.</u>

RECOMMENDATION ON EXPERIMENTS

- SHOULD BE SELECTED BY CONSENSUS.
- MOST WILL PROBABLY BE USED INITIALLY FOR CODE CALIBRATION, & WILL PLAY A ROLE LATER IN CODE VALIDATION
- IT IS IMPERATIVE TO OBTAIN DETAILED MEASUREMENTS IN THE FLOW FIELD
- NASA SHOULD ADOPT, AS A CENTRAL PART OF VALIDATION EXPERIMENTS, THE MISSION OF DEVELOPING DIAGNOSTIC MEASUREMENT TECHNIQUES FOR GENERAL AND COMPREHENSIVE USE.

FLOW CATEGORIES RELEVANT TO SUBSONIC TRANSPORT AIRCRAFT

- COMPLEX GEOMETRIES WITH COMPLEX PHYSICS
- REYNOLDS NUMBER VARIATIONS (W.T. & FLIGHT)
- DRAG PREDICTION
- LOW SPEED HIGH LIFT SYSTEMS
- TRANSONIC CRUISE
- STABILITY & CONTROL AT PERIMETER OF FLIGHT ENVELOPE.

CFD ACTIVITIES AT MSFC

(VALIDATION)

L. A. SCHUTZENHOFER AND P. K. McCONNAUGHEY

N92-70954

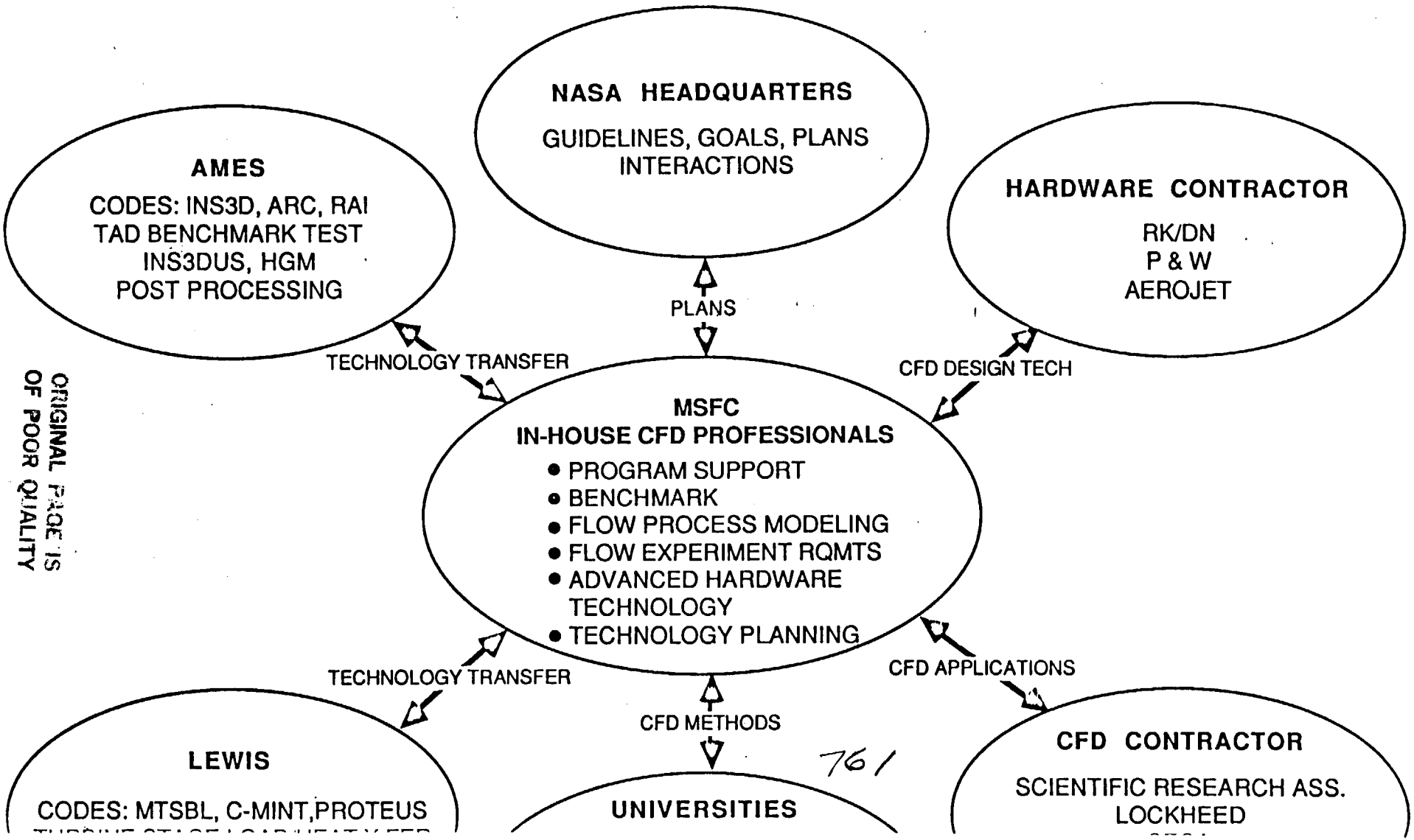
OVERVIEW

- CFD OBJECTIVES AT MSFC
- COOPERATING CFD ORGANIZATIONS
- CODES IN USE AT MSFC
- APPLICATIONS TO HARDWARE DEVELOPMENT
- MSFC BENCHMARK PLAN
- SUMMARY

CFD OBJECTIVES AT MSFC

- SUPPORT SPACE FLIGHT HARDWARE ISSUES
- DEVELOP IN-HOUSE CFD CAPABILITY
- BENCHMARK/EVALUATE CODES
- ORGANIZE AND MAINTAIN SOA DESIGN ORIENTED CFD CODES/CAPABILITY
- ADVANCE HARDWARE TECHNOLOGY

4-1428-7-12



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CODES IN USE AT MSFC

CODE	SOURCE	APPLICATION
INS3D	ARC	INTERNAL FLOW
ROTOR-1	ARC	ROTOR-STATOR
MTSBL	LeRC	TURBINE
PARC	AEDC/ARC	EXTERNAL/INTERNAL FLOW
DMSC	MSFC/BIRD	AFE
CMINT	SRA/LeRC	INTERNAL FLOW
PHOENICS	CHAM	SRB BORE AND JOINT FLOW
KIVA	LOS ALAMOS NAT. LAB.	COMBUSTION
EAGLE	MSU	GRID GENERATION
SVTGD3D	AEDC	GRID GENERATION
CAEDS	IBM	CAD/CAM/GRID INTERFACE
PLOT3D	ARC	GRAPHICS ON IBM AND IRIS

APPLICATION TO HARDWARE DEVELOPMENT

(IN-HOUSE CALCULATION)

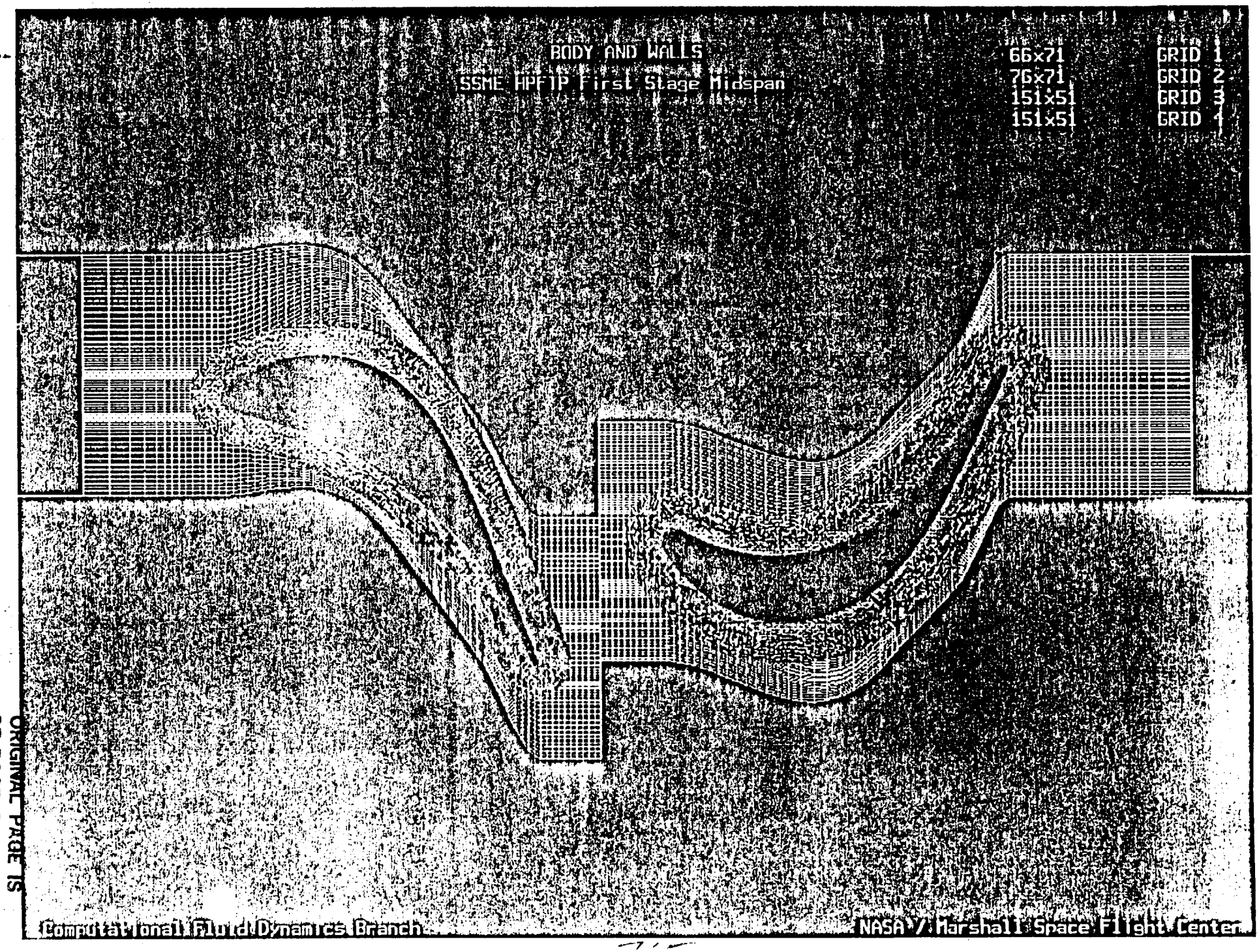
- SSME
  - FLIGHT ENGINES
    - *FUEL TURBINE BLADE LOADS AND HEAT TRANSFER ANALYSIS#
    - FUEL PUMP DISK CAVITIES AND COOLANT FLOW MODELING#
    - LOX PREBURNER
    - *LOX PUMP BEARING CAVITY
    - LOX PUMP COOLANT FLOW MODELING
    - LOX PUMP BEARING#
    - LOX TEE (4000 Hz)#
- SRB
  - BORE FLOW#
  - FIELD JOINT#
  - NOZZLE JOINT
- SPACE APPLICATIONS
  - *- AFE
  - *- VEHICLE PLUME CONTAMINATION

#RIG TESTS TO SUPPORT CALCULATIONS

MSFC APPLICATION OF AMES ROTOR-1 CODE

TO

SSME FIRST STAGE FUEL TURBINE



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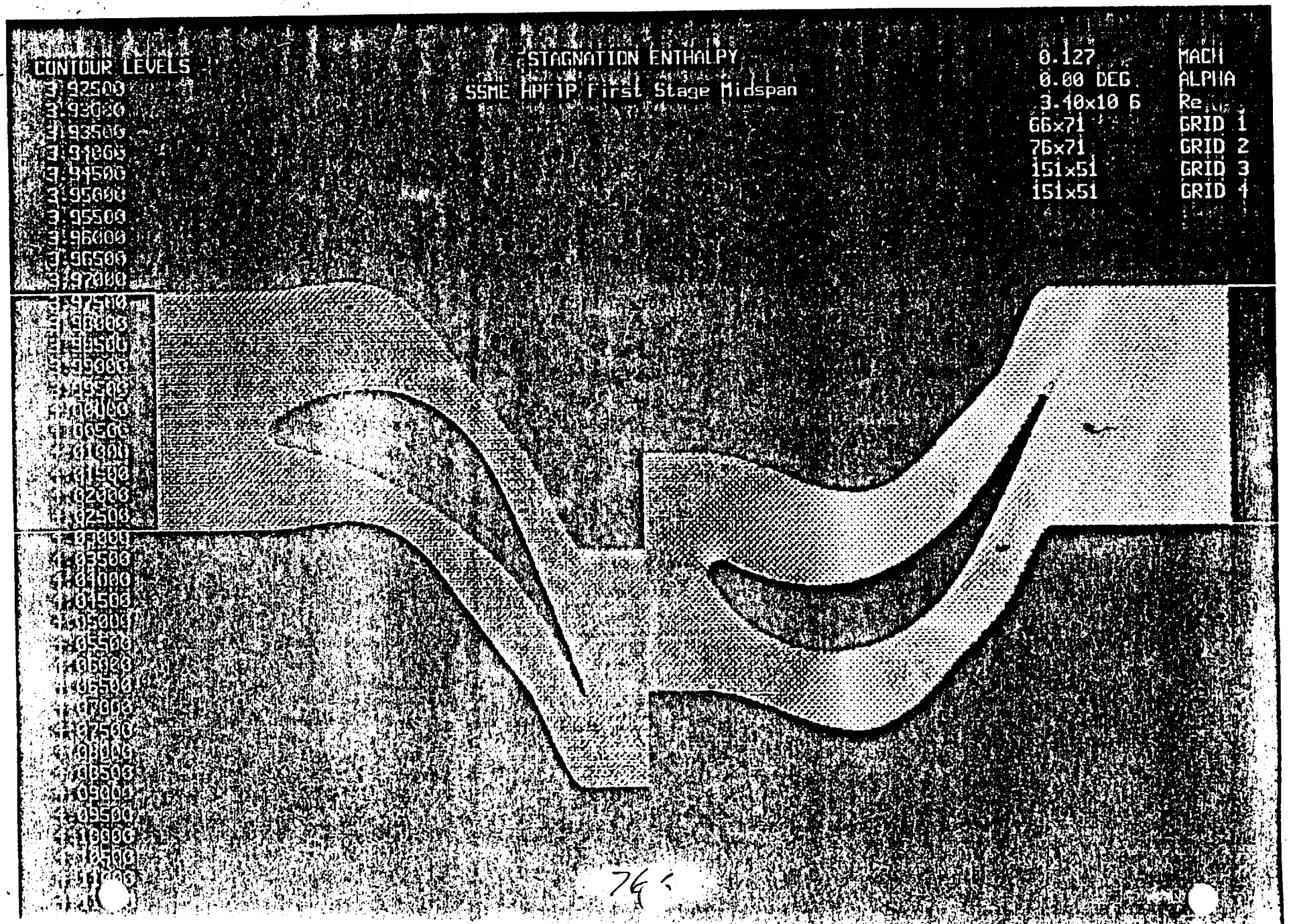
STAGNATION ENTHALPY
SSME HPFTP First Stage Midspan
CONTOUR LEVELS
0.127 MACH
0.00 DEG ALPHA
3.10x10 6 Re
66x71 GRID 1
76x71 GRID 2
151x51 GRID 3
151x51 GRID 4

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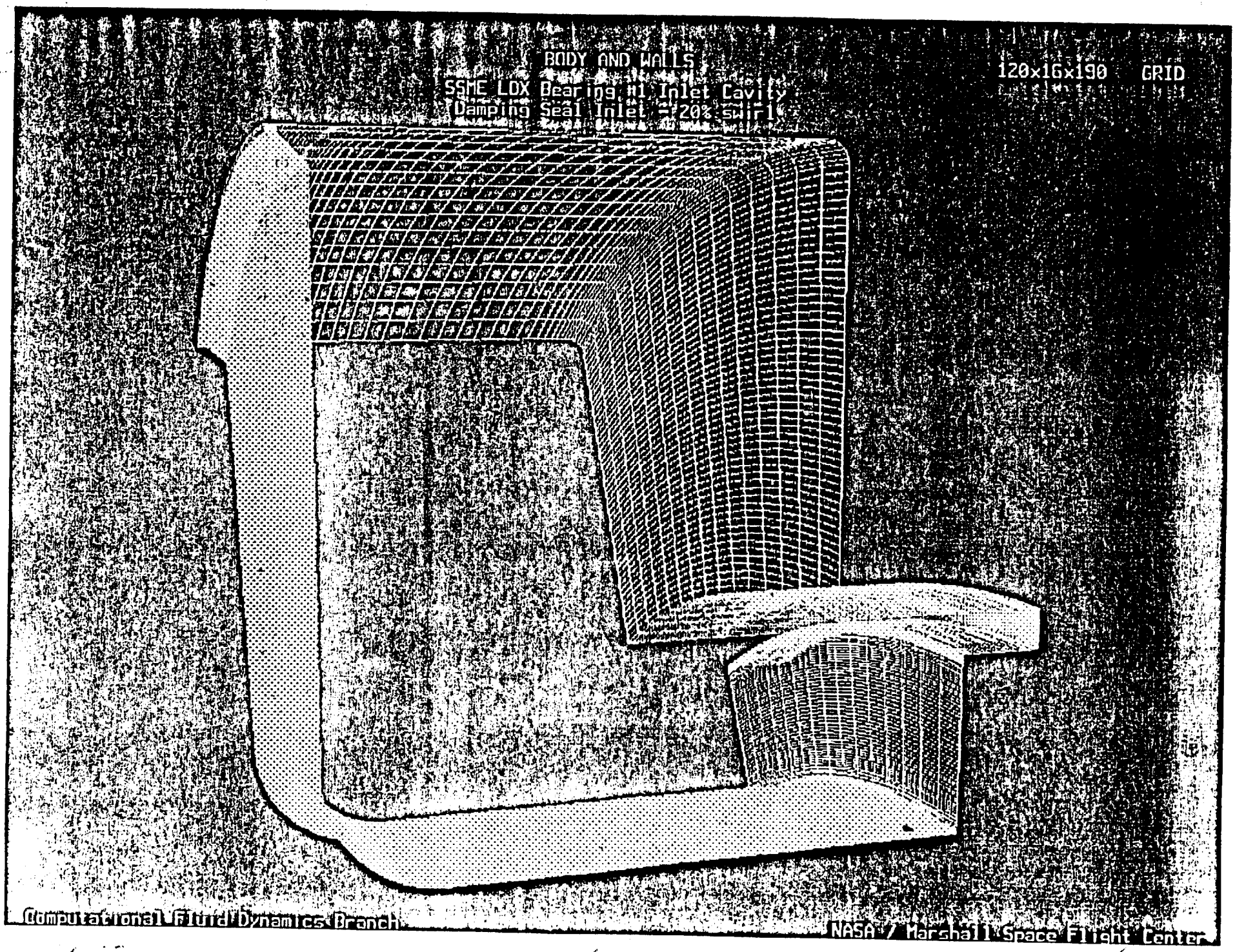
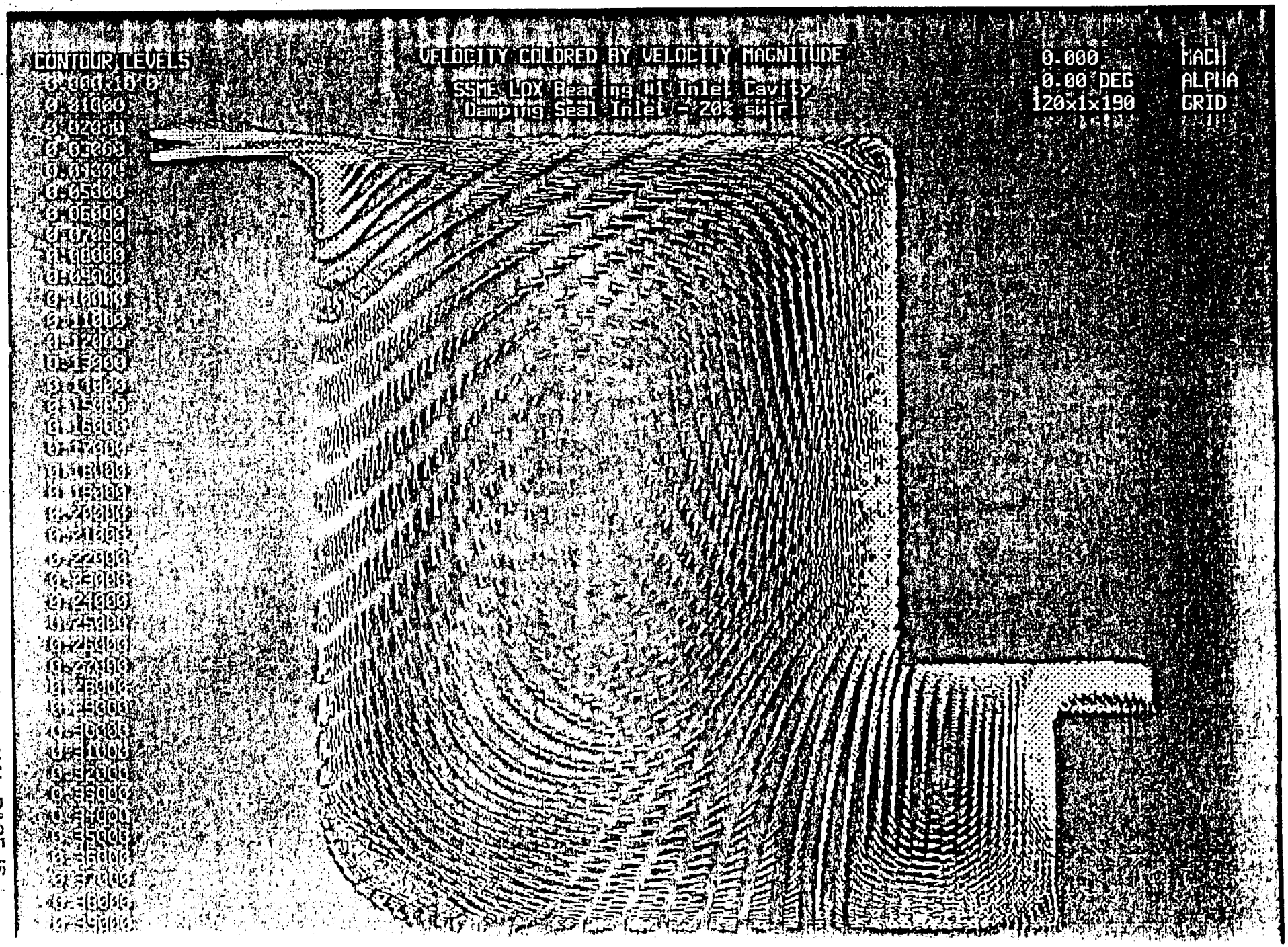
HPOTP BEARING NO. 1 CAVITY INLET


BODY AND WALLS
SSME LOX Bearing #1 Inlet Cavity
Damping Seal Inlet ≈20% swirl
120x16x190 GRID
Computational Fluid Dynamics Branch
NASA / Marshall Space Flight Center



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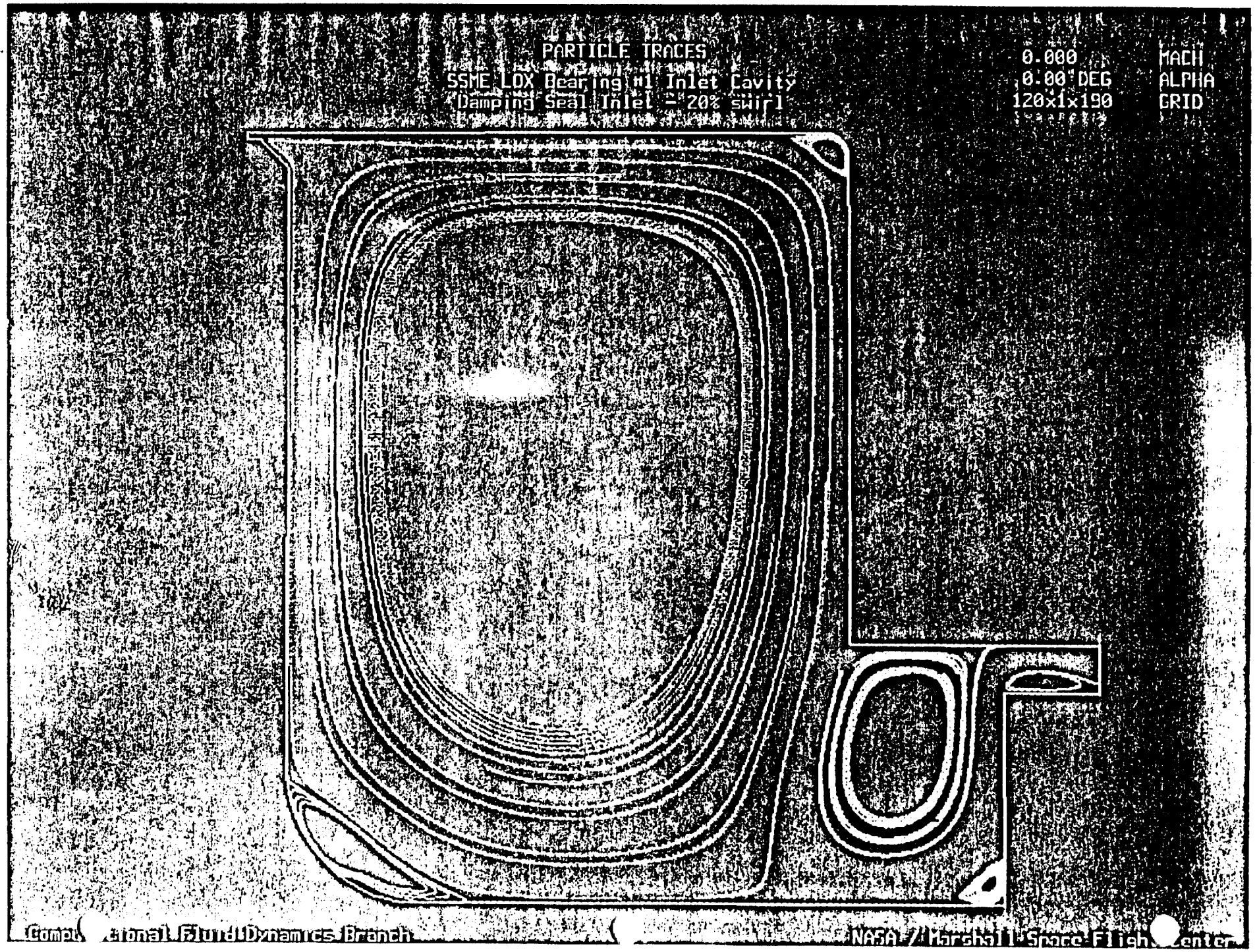
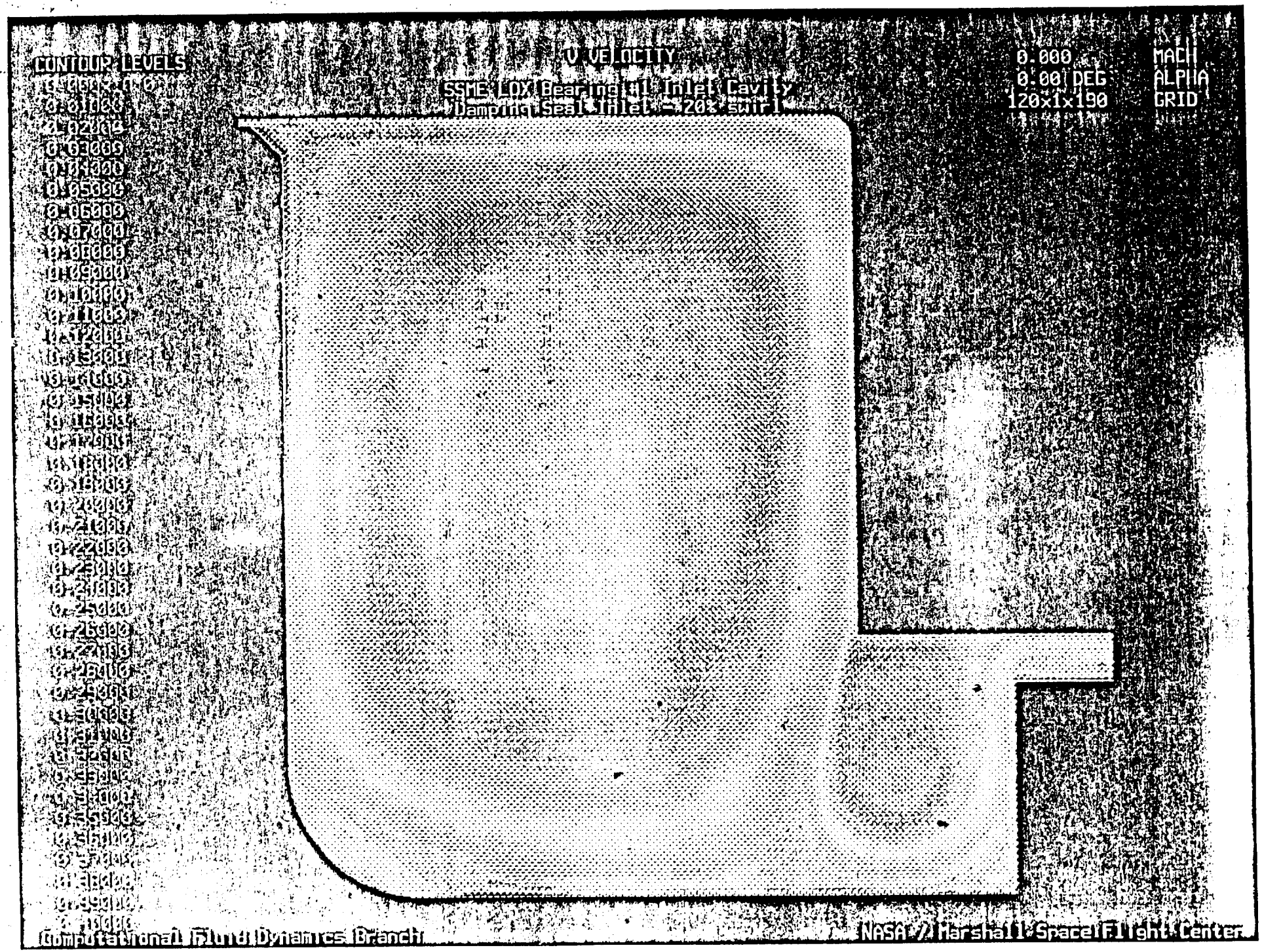

PARTICLE TRACES
SSME LOX Bearing #1 Inlet Cavity
Damping Seal Inlet - 20% swirl
0.000 MACH
0.00 DEG ALPHA
120x1x190 GRID
Computational Fluid Dynamics Branch
NASA/Marshall Space Flight Center



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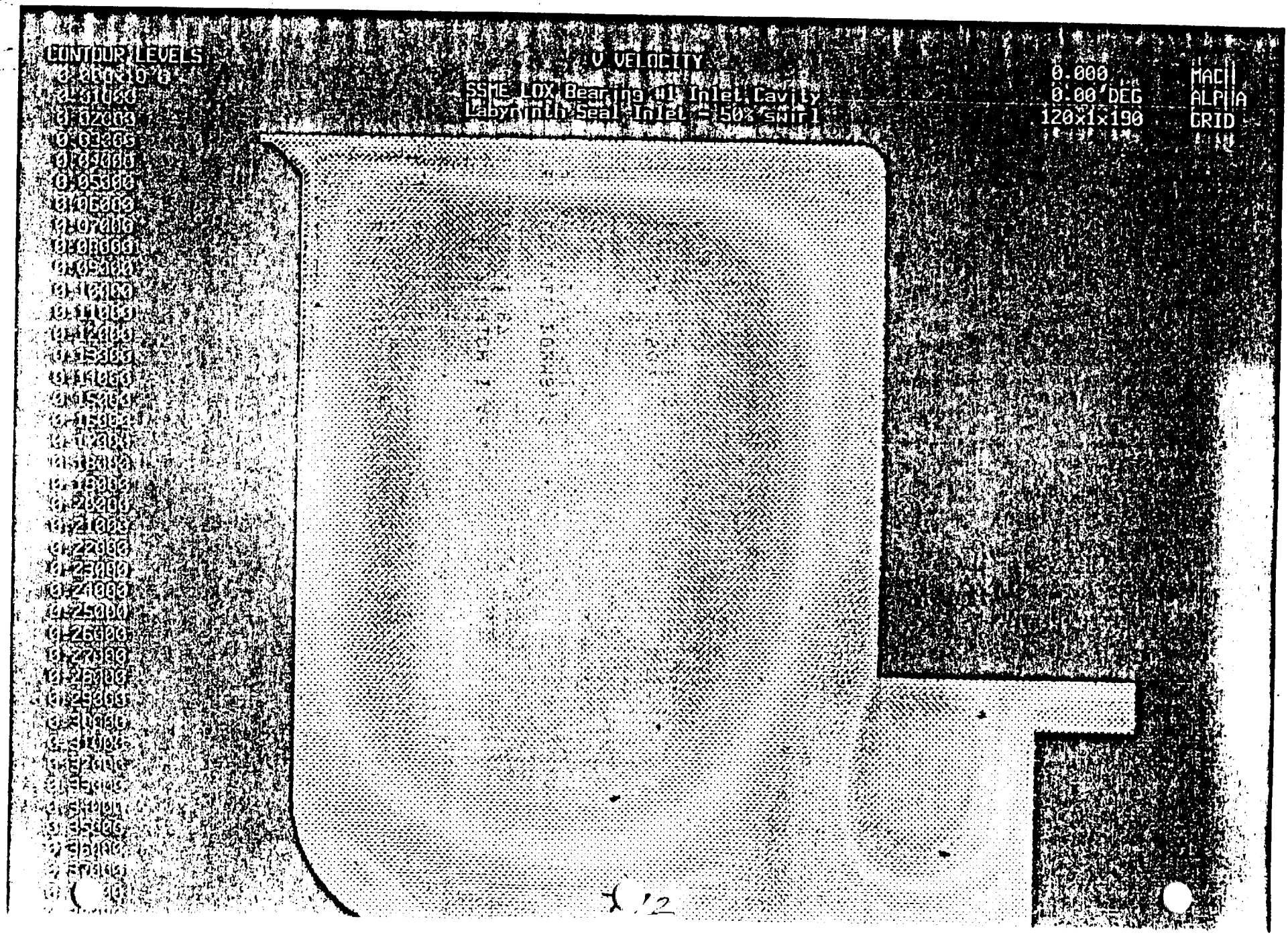
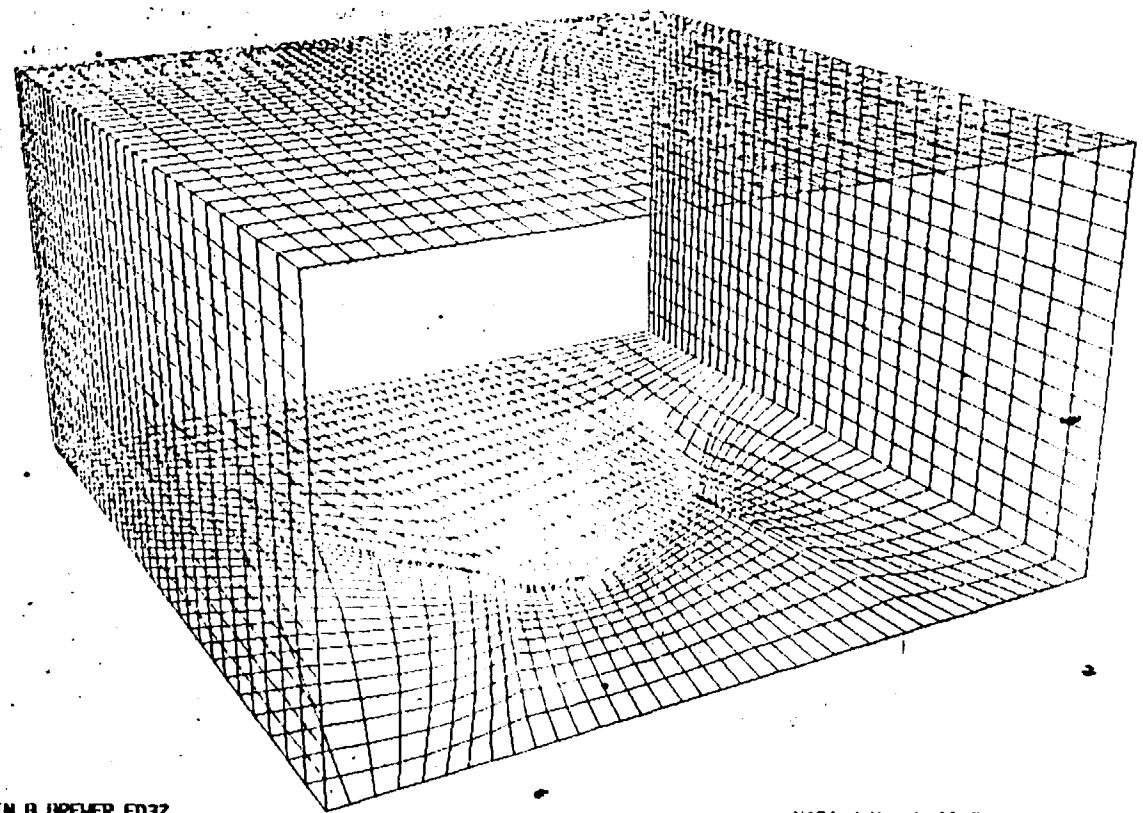

CONTOUR LEVELS
V VELOCITY
SSME LOX Bearing #1 Inlet Cavity
Labyrinth Seal Inlet = 50% swirl
0.000 MACH
0.00 DEG ALPHA
120x1x190 GRID

DSMC AFE SIMULATION

BODY AND WALLS

DIRECT SIMULATION MONTE CARLO
AEROASSIST FLIGHT EXPERIMENT

34x40x16 GRID



EDWIN B BREWER ED32

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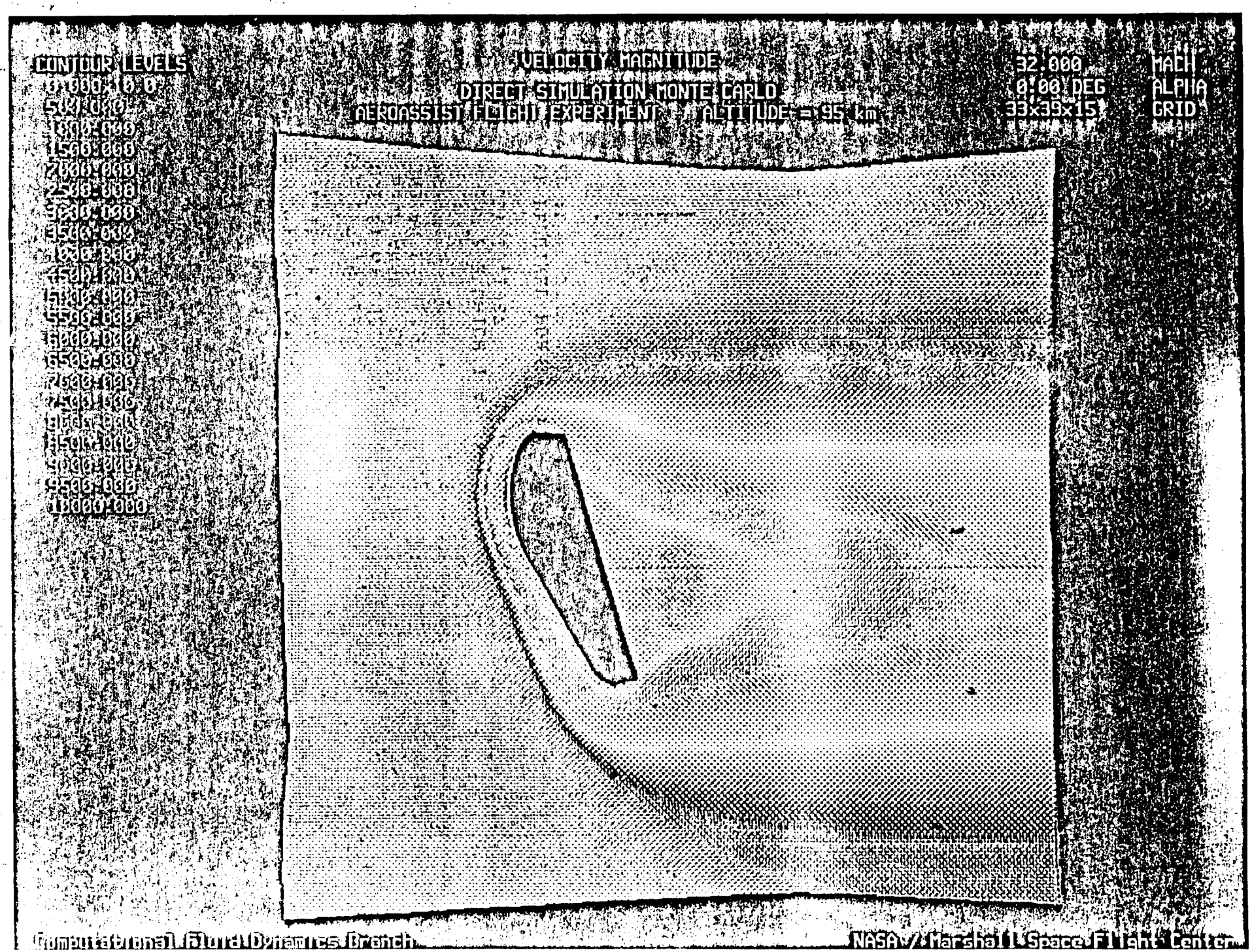

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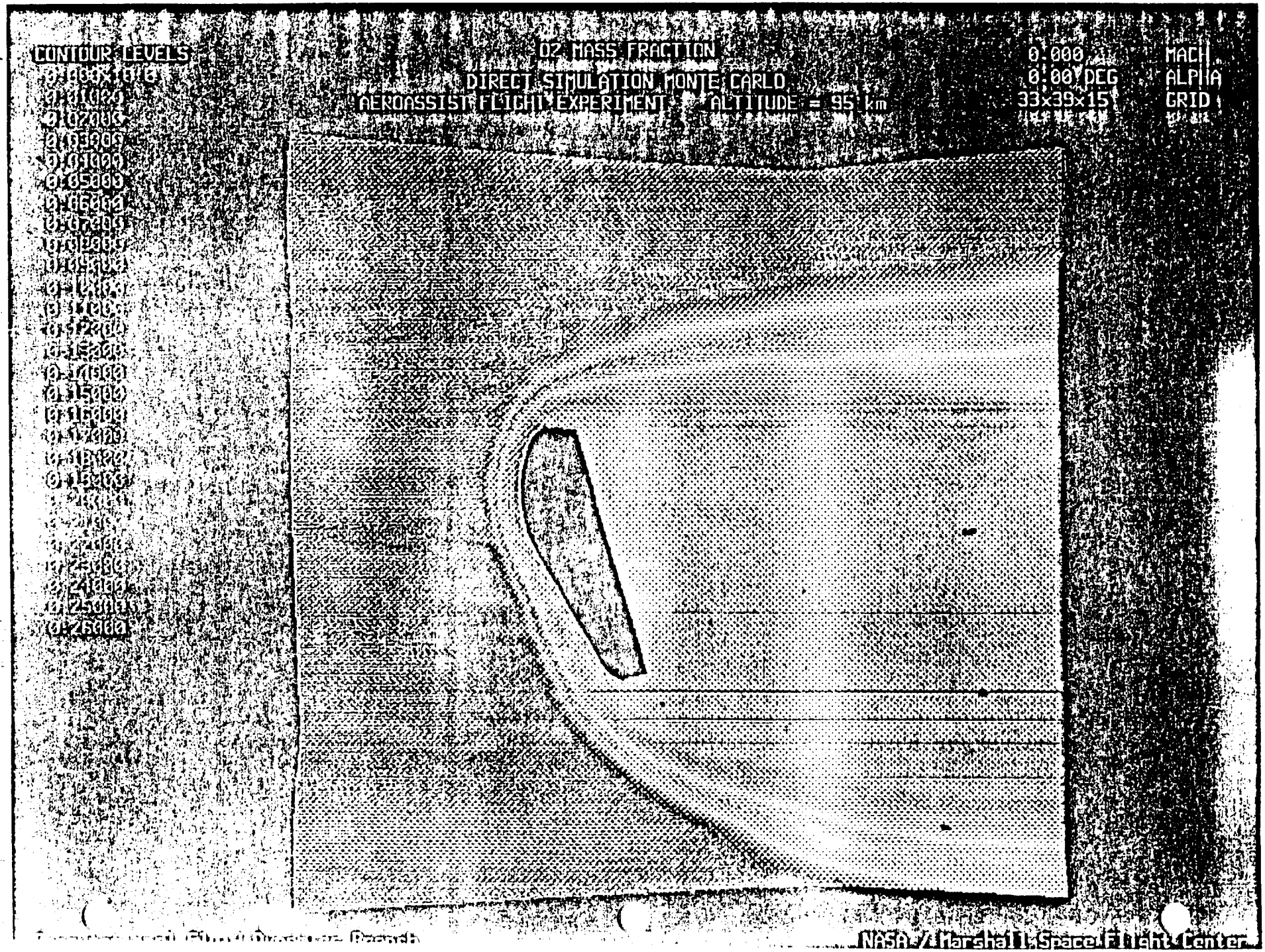
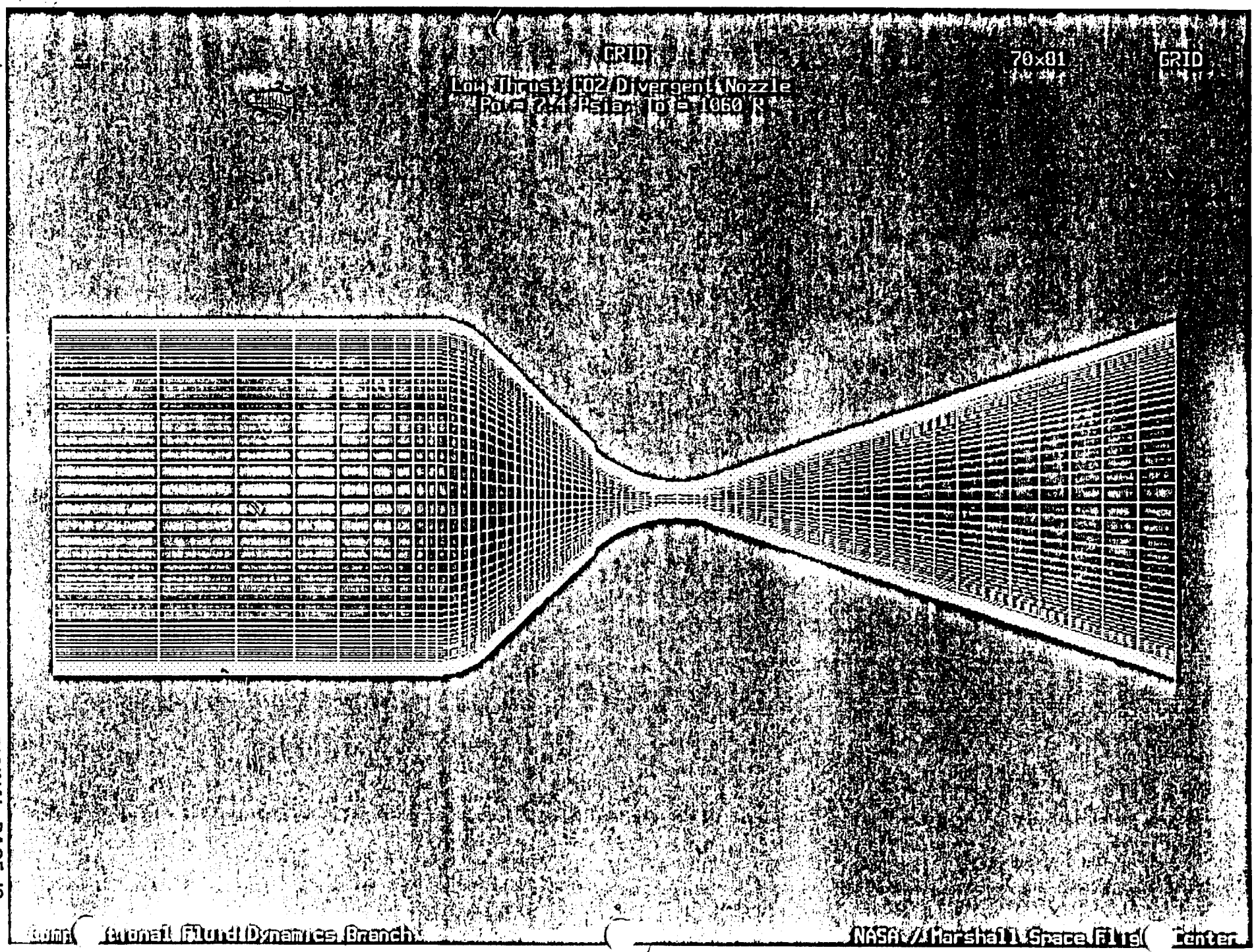


NASA/Marshall Space Flight Center

VEHICLE CONTAMINATION STUDIES

LOW THRUST CO_2 NOZZLE



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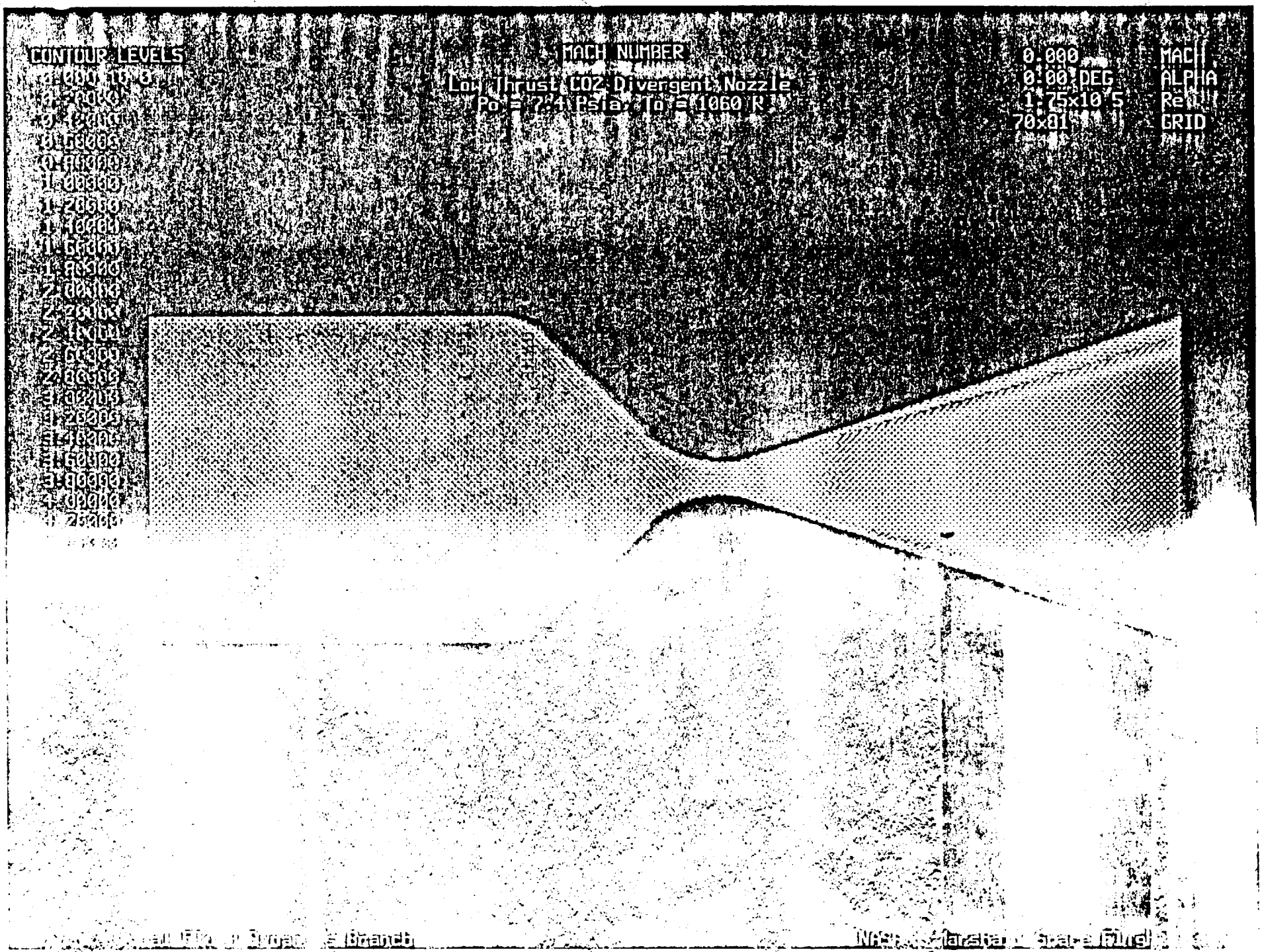

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MSFC BENCHMARK PLAN

- PROPOSED BENCHMARK LEVELS OF COMPARISON

  - LEVEL 1
    - A. PREDICTION OF THE INSTANTANEOUS THERMODYNAMIC AND KINEMATIC CHARACTERISTICS OF THE FLOW FIELD
    - B. PREDICTION OF THE STATISTICAL CHARACTERISTICS RELATED TO THE THERMODYNAMIC AND KINEMATIC FLOW PROPERTIES
  - LEVEL 2
    - A. ACCURATE PREDICTION OF THE MEAN FLOW CHARACTERISTICS, e.g., VELOCITY/PRESSURE PROFILES, SEPARATION POINTS, ETC.
    - B. ACCURATE PREDICTION OF REYNOLDS AVERAGED UNSTEADY NAVIER-STOKES EQUATIONS, e.g., ACOUSTICS, TRANSIENTS
  - LEVEL 3
    - PREDICTION OF THE GENERIC FLOW FIELD CHARACTERISTICS AND TRENDS ALONG WITH REASONABLE BOUNDS ON THE THERMODYNAMIC AND KINEMATIC PROPERTIES

MSFC BENCHMARK PLAN

PROBLEM	LEVEL
LeRC HOST DUCTS	2
ARC TURNAROUND DUCT	2
HGM PILOT MODEL	2
HGM (WATER, AIR, TTB)	2, 3
UTRC TURBINE BLADES	2, 3
UTRC DISK CAVITIES	2, 3
STANFORD CONFERENCE/LITERATURE	2
SRB JOINT AND BORE FLOW	2, 3
AFE	2, 3
PLUME CONTAMINATION	3

SUMMARY

- PRIMARY FOCUS OF CFD ACTIVITIES AT MSFC
  - DEVELOP IN-HOUSE CAPABILITY ORIENTED TOWARD HARDWARE APPLICATIONS
  - EVALUATE AND BENCHMARK CFD TECHNOLOGY FOR MSFC HARDWARE APPLICATIONS

VI. SMALL WORKING GROUP REPORTS

DO NOT TAKE

GROUP A

Low Speed Aerodynamic Flows

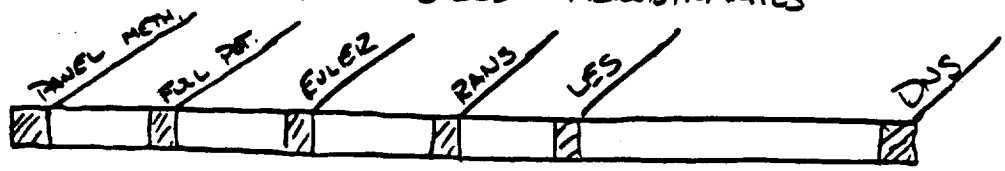
Bldg. 258 / Rm. 111

Suggested Spokesperson : J. South

L. Chow
S. Davis
D. Driver
S. Kjelgaard
R. Margason
R. Mehta
A. Nakayama
S. Robinson*
M. Rubesin
A. Thomas
~~W. Whitlow~~
~~N. Wood~~
J. Hess

* Guide and room coordinator

COMPUTATIONAL METHODS CURRENTLY IN USE FOR ANALYZING LOW SPEED AERODYNAMICS



→ NASA CODES;
ARC2D; INS3D; CFL3D; VORSDI; KIM/MOIN

AREAS THAT SHOULD BE WORKED IN NEAR FUTURE

1) JET IN CROSS FLOW
2) 2-D WING AT HIGH ALPHA (3-D MEASUREMENTS)
3) 3-D WING AT HIGH ALPHA
4) BODY OF REVOLUTION AT ANGLE OF ATTACK
5) DYNAMIC STALL
6) DELTA WING VORTEX FLOWS
   a) EVOLUTION
   b) BREAKDOWN
   c) INTERACTION
7) WALL JETS
8) ROTOR INFLOW / WAKE
9) BLADE VORTEX INTERACTION
10) STEP FLOWS
11) SHEAR FLOWS
12) TRANSITION

LOW SPEED CODE VALIDATION WORKSHOP GROUP

AREAS PRESENTING NEEDS FOR
CODE DEVELOPMENT / VALIDATION

CONFIGURATION
- TRANSPORT
  - TRANSITION
  - FLOW SEPARATION
  - INLET FLOWS
  - MULTI-ELEMENT AIRFOIL
- FIGHTERS
  - HIGH-α VORTEX FLOWS
    - INTERACTIONS
    - BURSTING
  - ASYMMETRIC VORTEX FLOWS
- HIGH ALTITUDE
  - TRANSITION
  - LOW RN AERODYNAMICS
- REMOTE POWERED VEHICLES
  - LOW RN AERODYNAMICS

POWERED HI-LIFT
- JET IN CROSS FLOW
- JET IN GROUND EFFECT
- CIRCULATION CONTROL
- EJECTOR FLOWS
- HI α AERODYNAMICS
- FLOW SEPARATION

ROTOR CRAFT
- ROTOR INFLOW
- BLADE / VORTEX INTERACTION

ISSUES TO BE ADDRESSED FOR EACH FLOW VERIF. FAMILY

1. KNOWLEDGE OF TRANSITION LOC. & EXTENT
2. WHAT ARE CRIT. PARAMS?
3. WHAT FLOW QUAL. & MEASUREMENTS REQ'D?
4. CAN EXPS. BE APPLICABLE TO OTHER FAMILIES OR TECHNOLOGY AREAS?
5. REDO SOME PREVIOUS EXPS?
6. CAN AN EXP OF CLASS A,B,C FULFILL PART OF REQMTS OF NEXT HIGHER CLASS?
7. RECOMMEND STANDARDIZED TEST CASES?

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RECOMMENDATIONS:

- FORM SUBCOMMITTEES FOR EACH EXPER.'L FAMILY
  - INCLUDE EXPERIMENTAL + COMP'L PRINCIPALS
  - ACTIONS : SURVEY + ASSESS EXISTING DATA + NEEDS
    : ADDRESS CFD VAL. ISSUES [LISTED PREVIOUSLY]
    + OTHERS AS APPROPRIATE

- DEDICATE A LARGE-SCALE TEST FACILITY TO FUNDAMENTAL CODE VALIDATION EXPERIMENTS
  - FLOW QUALITY MUST BE HIGH
  - FLOW QUALITY/TUNNEL CHARACTERISTICS MUST BE WELL DOCUMENTED

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GROUP B

High Speed Aerodynamic Flows
Commercial

Bldg. 229 / Rm. 215

Suggested Spokesperson: P. Rubbert

R. Barnwell
T. Coakley
W. Harvey
J. Lee
D. Johnson
J. Malone
G. Mateer*
J. McCroskey
T. Pulliam
L. Putnam
K. Rogers
M. Salas
L. Seegmiller
P. A. Wilcox
L. Roberts

* Guide and room coordinator

FOCUS - GROUP B

(HI SPEED AERO FLOWS ~ COMMERCIAL)

CONVENTIONAL TRANSPORTS

NOT ADDRESSED:

- SUPERSONIC
- HIGH α
- V/STOL
- ROTORCRAFT
- INTERNAL FLOWS

TOP/DOWN FOR TRANSPORTS

1. FLOW REGIMES OF INTEREST
   - CRUISE
   - HIGH LIFT (LANDING & TAKEOFF)
   - PERIMETER OF FLIGHT ENV (S & C)
   - BOUNDARY OF CRUISE-TYPE FLOW (BUFFET BDRY, ETC).

2. GEOMETRIES OF INTEREST
   W/B
   + THL, WINGLETS, OTHER LIFTING SURFACES
   + PROPULSION SYSTEM
   + FLAP TRACK FAIRINGS, ETC
   + FLAPS
   + EXCRESCENCES,

MAJOR HOLE ~ LACK OF VALIDATION EXPERIMENTS AT FLIGHT Re_r

#2 CRITICAL PROBLEM AREAS

(a) BASIC FLUID MECHANICS

- DETAILED CLEAN WING AERODYNAMICS
- CAVITY FLOWS
- Re EFFECTS
- AIRFOIL IN A CHANNEL. DO 2-D & 3-D CFD
- SEPARATED FLOW
- TRANSITION
- LACK OF COMPLETE DATA SET FOR ANY FUNDAMENTAL EXPERIMENT
- SHOCK/B.L. INTERACTION & SEPARATION
- KNOWLEDGE OF R.C.'S IN EXPERIMENT
- DEV. OF INSTRUMENTATION.
- DEFINE LIMITS (MOUNTING) IN SUPERSONIC FLOW UNDER WHICH LAMINAR FLOW CAN BE ACHIEVED.
- ERROR BANDS OF INSTRUMENTATION
- REDUNDANT VERIF.
- IDENTIFY THE CRITICAL MEASUREMENTS
- FOCUS ON 3-D UNSTEADY MEASUREMENTS (WITHIN DOMAIN OF UNSTEADINESS)
- TREAT WALL & MOUNTING SYSTEM AS PART OF THE MODEL, & UPSTREAM/DOWNSTREAM

#2 CRITICAL PROBLEM AREAS
(b) AIRPLANE ORIENTED ~ TOP/DOWN

- NEED FLIGHT TEST ~ RIGHT DATA
- R_e EFFECTS
- DEV. OF INSTRUMENTATION
- IDENTIFY THE DOMINANT PHYSICS THAT CONTROL THE OVERALL FLOW & THE MAJOR AERO PARAMETERS.
- ERROR BANDS OF ~~INSTRUMENTATION~~ MEASUREMENTS
- REDUNDANT VERIF.
- IDENTIFY THE CRITICAL MEASUREMENTS.
- $C_{L_{max}}$ PREDICTION AT LOW SPEED
- FOCUS ON UNSTEADY MEASUREMENTS (3-D) (DEFINE DEGREE OF UNSTEADINESS)
- COMPONENT BUILDUP
- TREAT WALL & MOUNTING SYSTEM AS PART OF THE MODEL, & UPSTREAM/DOWNSTREAM
- DEFINE MINIMUM DATA REQUIRED.
- FLOW FIELD MEASUREMENTS

PRINCIPLES

1. ATTEMPT A COMPUTATION PRIOR TO FREEZING THE EXPERIMENT.
   - DEFINITION OF OUTER B.C. MEASUREMENTS REQUIRED
   - SENSITIVITY TO CHANGES IN PARAMETERS – IDENTIFY BIG SWINGERS & LESS IMPORTANT ITEMS.

   CFD SHOULD BE TREATED AS PART OF THE EXPERIMENT.

2. MUST MEASURE MODEL & CONFIGURATION GEOMETRY & AEROELASTICS.

TOP / DOWN

MEASUREMENTS

WINGS (CRUISE & BUFFET)

- TRANSITION LOCATION
- 3-D BOUNDARY LAYER MEAN PROFILES
  - ALONG TRAILING EDGE
  - AHEAD OF SHOCK
  - BEHIND SHOCK
  - BOTH MEAN & FLUCTUATING QUANTITIES
  - SURFACE VIZ.
  - SHOCK SHAPE, EXTENT, LOSSES!
- SURFACE PRESSURES
- GEOMETRY OF WING
- DOWNSTREAM WAKE

TOP DOWN MEASUREMENTS

BODY

BOUNDARY LAYER
SURFACE PRESSURES
SURFACE FLOW VIZ
WAKES

~~WING/BODY INTERSECTIONS~~ JUNCTION
~~& TAIL INTER~~

JUNCTURE FLOWS

PROPULSION MEASUREMENT

SURVEYS OF EFFUX & INFLOW
VELOCITY DISTRIBUTION
SURFACE PRESSURES
SURFACE FLOW VIZ

6

TOP DOWN MEASUREMENTS

HIGH LIFT

CONFLUENCE
SEPARATION
VORTICES
UNSTEADY
=
=
=

OVERALL

DRAG
THRUST
LIFT
~ MEASUREMENTS TO RECONCILE A MOMENTUM BALANCE

KEY RECOMMENDATIONS

1. UNIFIED CFD/EXP FROM THE VERY BEGINNING

2. MUST MEASURE ALL BOUNDARY CONDITIONS, ETC.

3. DO CFD PRIOR TO DESIGNING EXPERIMENT. USE CFD FOR SENSITIVITY ANALYSIS.

4. INVEST IN DIAGNOSTIC TECHNOLOGY & IMPROVEMENT OF TESTING PRODUCTIVIT

5. CFD VALIDATION SHOULD BE A CONTINUIN PROGRAM & NOT ONLY A ONE-SHOT TRY.

6. INDUSTRY SHOULD DO MORE IN TERMS OF SHARING WITH NASA & ACADEMIC OF WHAT ISSUES WE FACE, & VICE-VERSA.

7. MAJOR HOLE IN LACK OF FLIGHT RE CORE VALID. INFO. GROUP EXPRESSED CONCERN OF ECONOMIC VIABILITY OF RECOMMENDING FLIGHT MEASUREMENTS.

8. FOCUS ON CRITICAL COMPONENT PHYSICS – SEE ATTACHED LIST

9. PRIORITY RECOMMENDATIONS

1. CRUISE WING, AT TYPICAL WIND TUNNEL & FLIGHT Re.

2. WHATEVER IS SENSIBLE TO DO IN HIGH LIFT.
   - MULTI-ELEMENT AIRFOIL, WHICH PHYSICS MEASURED, & WIND TUNNEL & FLIGHT Re.
   - GLOBAL STRUCTURE OF FLOW ON 3-D WING?

3. FUSELAGE BOUNDARY LAYERS HIGH & LOW R_e, DETAILED PHYSICS BUILDUP INCLUDING WING & TAIL JUNCTION

V. JUNCTURE FLOWS

GROUP C

High Speed Aerodynamic Flows

Military

Bldg. 229 / Rm 117

Suggested Spokesperson: H. Yoshihara

P. Bobbitt
J. Brown*
~~M. Buck~~
L. E. Ericcson
M. George
W. Henderson
T. Holst
G. Howell
~~G. Hall~~
J. Murphy
C. Nietubicz
M. Olsen
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J. Seiner
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*Guide and room coordinator

D. JASPER
J. TIPP
N. Wood
W. Whitlow, Jr.

High Speed Aerodynamic Flows-Military

Chaired by H.Yoshihara and P.Bobbitt

CFD Validation Workshop
July 14-16, 1987
NASA Ames Research Center, Moffett Field, CA 94035, USA

I. Key Efforts (Numerical and Experimental)
Immediate Modeling and Validation needs.

II. Near and Far Term Problem Areas requiring New models and Validation Activities.

III. New Computer, Experiments, Facilities, and Instrumentation for item II.

IV. Cooperative Model and Validation Projects.

V. Standard Test Cases.

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Preliminary: Identify Products and Important Fluid Dynamic Elements

1. **Transonic Fighter**

   Cruise and maneuver. Predict pressure distribution, Drag, moments.

   - Shock/boundary-layer interaction separation.
   - Base Drag w propulsion on. Includes Aftbody, jet exhaust interaction.
   - Powered lift.
   - Vortex/Bursting.
   - Inlet/nozzle.
   - Aeroelasticity/flutter.
   - Separation Buffet.

2. **STOVL**
   - Low-speed performance.
   - Power-jet interaction w surfaces.

3. **Stores**
   - Carriage
   - Release(dynamic)

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I. Key Efforts (Numerical and Experimental

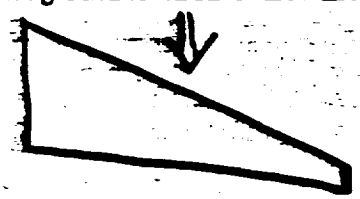
Immediate Modeling and Validation needs.

I1. Key Area: 3D Turbulence Modeling (Separation)

A. Transonic shock-induced boundary-layer separation

may not get immediate results but represents immediate need.

Tensor modeling rather than scalar modeling.



B. Other Separation

Leading-edge

Trailing-edge

Forebody

etc.* (where * Forward-facing surfaces, and * Cavities.)

Turbulence modeling where biggest problem occurs.

C. Wakes/Jet Mixing/Vortex Core

Predict Vortex bursting. May be unsteady but averageable.

Vortex may meander in experiment.

D. Aftbody Flowfields/Thrust-Vectoring/Tail or no-tail

I2. Key Area: Unsteady Flows (Turbulence and Flow Modeling)

Longer term requirement than above

Attached flows w/ inviscid(possibly potential) methods applicable of interest to aeroelasticity.

III. New Computer, Experiments, Facilities

- 3D LDV's needed. but instrument needs development and accuracy.
- Laser Induced Fluorescence. Iodine(dangerous) and Hydroxyl radicals(can put in wind-tunnel).

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IV. Cooperative Model and Validation Projects

- Focus on standard Cases.
- Need to move both Model and Support system(to greatest possible degree.)

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V. Standard Test Cases

Primary purpose is to validate code.

Test Cases should have:

1. Simple Geometry.
2. Redundancy of experiment, more than one facility.
3. Redundancy of instrumentation.
4. Available configuration and data. NOT Proprietary.

Data needed:

1. Oil flow.
2. Forces and moments.
3. C_p, C_f
4. Velocity profiles
5. unsteadiness issue?

   Near term - measure mean flow and experimenter to attempt to characterize unsteadiness if unsteadiness exists.

   Far term?

Test Cases Discussed:

A. Swept Wing (Forward and Backward sweep)

- Olsen(Ames-HRCII), 10-inch span and chord. Can add fuselage and strake. Wall boundary-layer effects may be problematic with different wind-tunnels.
- Pathfinder 2. High-Reynolds number.

B. Delta Wing.

- 75° Delta. 18 inch to 2 foot span so can move to other tunnels. Ongoing at Langley and Europe.

C. Wing/Fuselage.

- Erickson DoubleDelta or Strake/Delta.

D. Complete Fighter.

- X-29, 2.5 foot sized to go to $\alpha = 60°$ in NTF. Can move to other tunnels.

E. Aftbody

- Axisymmetric Aftbody-tail-jet.

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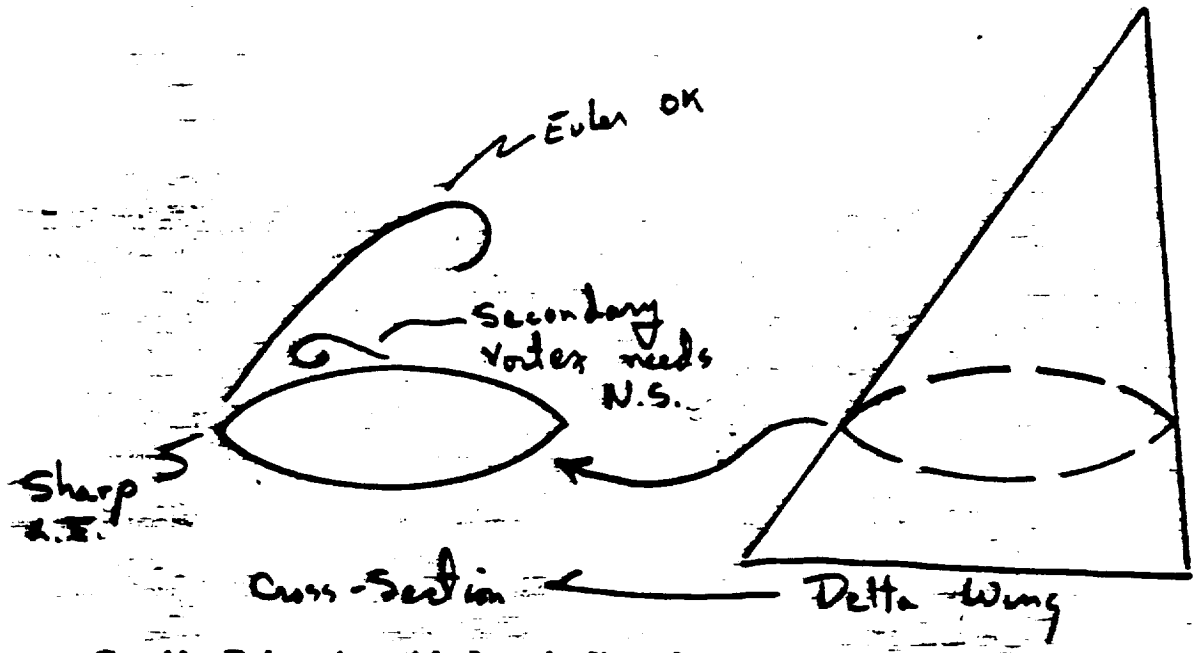
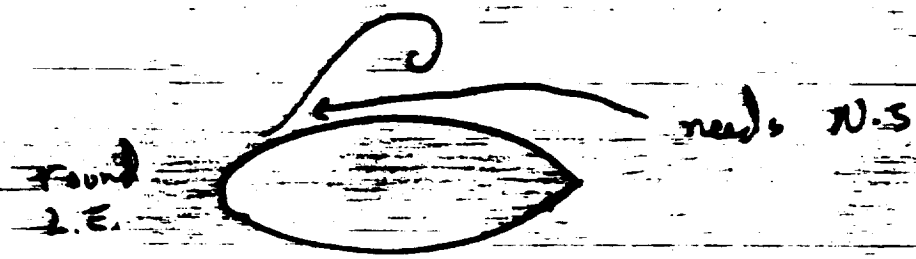
Remarks on computer code requirements for LE Vortex



- Consider Delta wing with sharp leading edge.
  Euler Code may be OK for primary leading-edge vortex. At low speeds, secondary vortex will be minor. If secondary vortex significantly affects pressure distribution then Reynolds number effects appear and will need Navier-Stokes code.



- Consider Delta wing with rounded leading edge. Reynolds number effects will occur since vortex formation defined in boundary layer and will need Navier-Stokes.

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Menu of Codes?

- Inviscid. Establish limits of applicability.
  - Panel methods
  - Small Disturbance methods
  - Potential Flow codes.
  - Euler Code
- Viscous.
  - Coupled Boundary-Layer/Inviscid methods.
  - Reynolds-Averaged Navier-Stokes.

Comment: There exists problems too complex to reasonably address at present.

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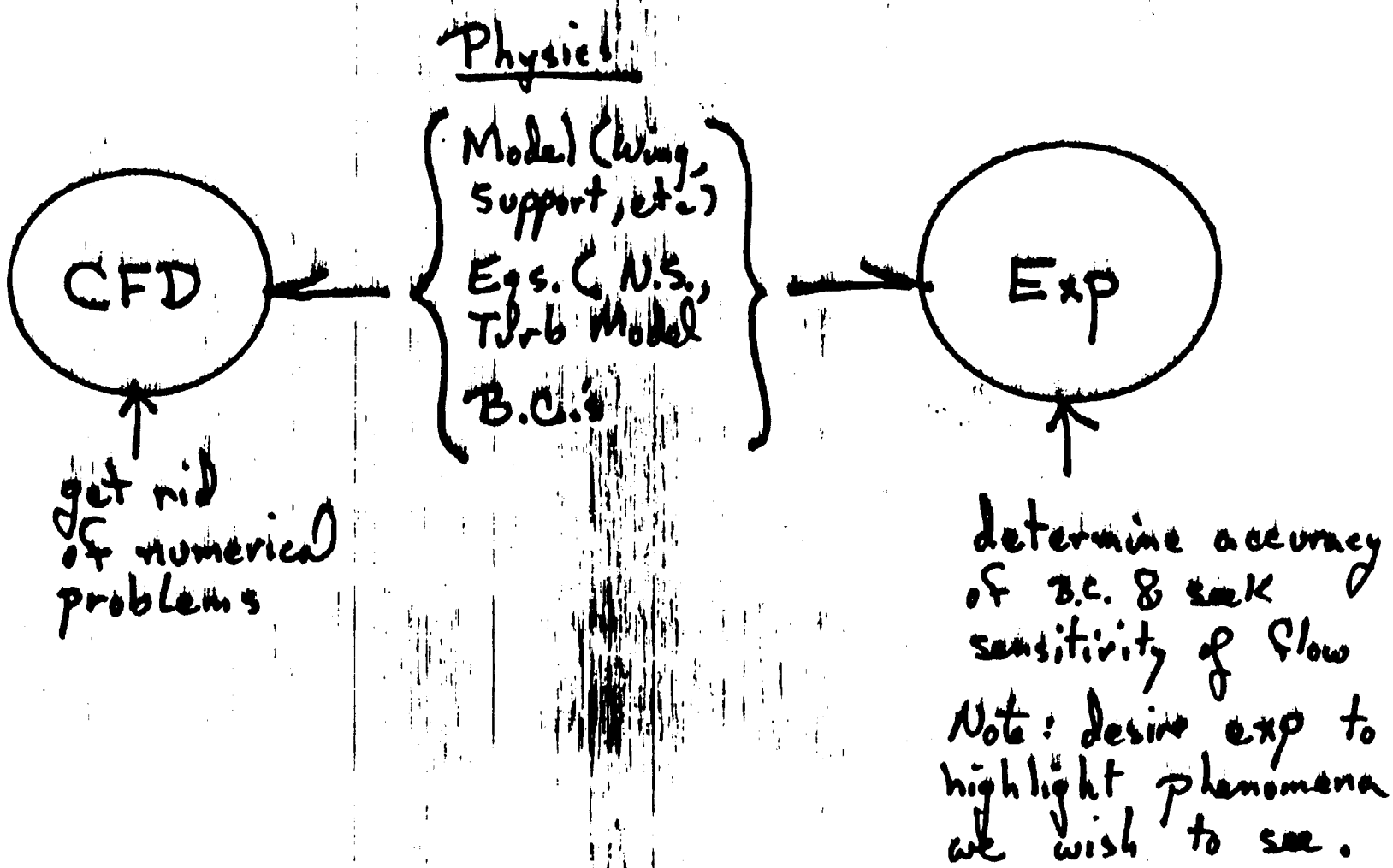
CFD / Experiment Interaction



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PRESENTATION — BOBBITT

FLOW PHENOMENA

- VORTEX FLOWS
  - ORIGINATION, GROWTH, BREAKDOWN
  - MULTIPLE VORTEX INTERACTIONS
  - LEADING EDGE
  - FOREBODY
  - WING TIP
  - JUNCTURE
  - WING NORMAL VORTICES
- FLOW SEPARATION
  - TRAILING EDGE
  - RAMP OR CONTROL SURFACE
  - LEADING EDGE BUBBLE
  - SHOCK INDUCED

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FLOW PHENOMENA (CONT'D)

- SHEAR LAYERS
- SHOCK / BL INTERACTION
- UNSTEADY FLOW
- JET MIXING
- TRANSITION
- TURBULENCE

REYNOLDS NO. EFFECTS ON ALL OF THE ABOVE

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FLOW FIELDS OF CONCERN

- WING/BODY, PYLON/WING, ETC. JUNCTURES
- FUSELAGE, STRAKE/CANARD AND WING VORTEX INTERACTIONS
- TIP FLOWS INCLUDING VARIOUS TIP DEVICES/GEOMETRIES
- WAKE
  - INFLUENCE OF WAKES ON DOWNSTREAM SURFACES
  - INFLUENCE ON INDUCED DRAG
- LEADING EDGE VORTEX — PRIMARY AND SECONDARY
- LEADING EDGE VORTEX BREAKDOWN

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FLOW FIELDS OF CONCORN

- INLET FLOW FIELDS
- AFTERBODY/JET-EXHAUST INTERACTION
- INTERNAL INLET FLOWS WITH DISTORTION
- INTERNAL NOZZLE FLOWS WITH THRUST VECTORING AND REVERSING
- MASSIVE FLOW SEPARATION (WING)

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BASIC EXPERIMENTS*

- JUNCTURE FLOWS
- Leading Edge VORTEX FLOWS (INCL. SECONDARY)
- 3D SHOCK/B.L. INTERACTIONS
- AFTERBODY/TAILS/JET INTERACTION
- Fuselage FLOWS
- INLET FLOWS
- CAVITY FLOWS

* REDUNDANCY DESIRABLE

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1. Wing - Body - Junction

→ Simple airfoil on plate on tunnel wall or on splitter

→ Subsonic, Transonic, Supersonic

→ leading edge sweep 65°, perhaps 0° - other later

→ rounded leading-edge radius. pick typical Re radius/chord.

→ Choose either with fillets or w/o fillets, not both at first

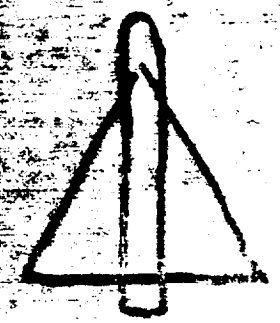
→ LEX - not now

→ Study Re # variation effects.

2. Leading-Edge Vortex

- Need 2 models

a) Wall-mounted
- large scale
- similar to junction flow model



b) Sting-mounted
- remove wall bl effects
- design codes more easily applied
- similar to configural test

> 65° Sweep — to conform to other expts

> Study leading-edge bluntness

> Vary α

> Vortex Control Flap?

> Vortex-burst

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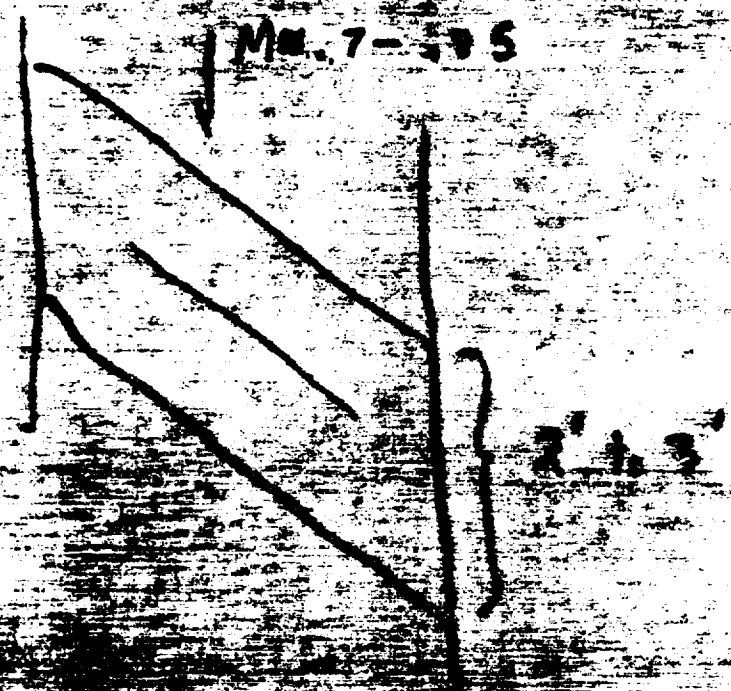
3. 3D Shock/BL Interaction

• Transonic, Yawed or Swept



> Interpolation to resolve B.L.

> Wall BL effect?

> Reynolds stresses

> Shock strength

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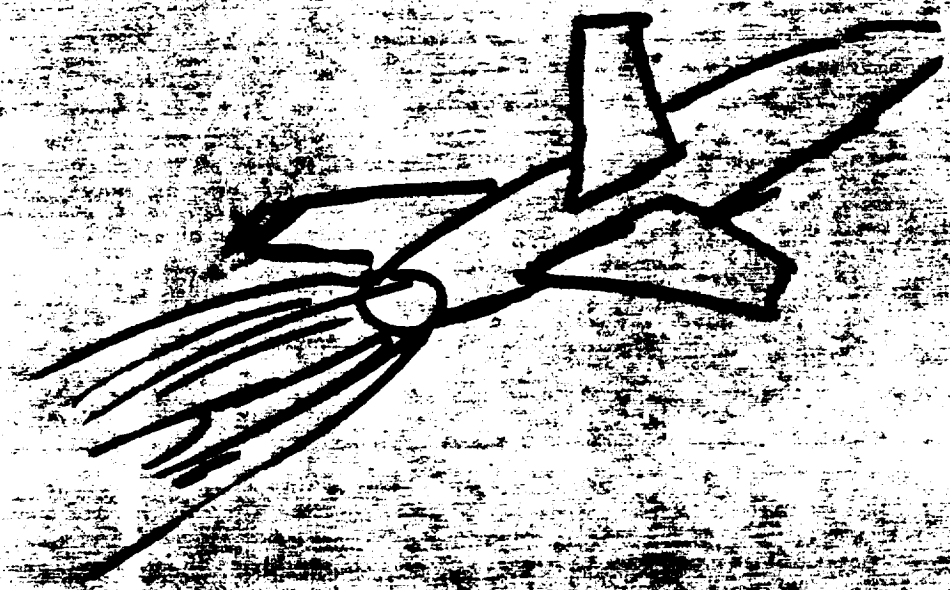
4. AFTERBODY/JET EXHAUST INTERACTION



- BOTH AND WO JET
  - TAILS
- JET EXHAUST/AFTERBODY BL AND INVISCID FLOW INTERACTION
  - SHEAR LAYER
- VARY PRESSURE RATIO & R.N.
- SUB TRANS AND SUPERSONIC
- UNSYMMETRIC IN PHASE II

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5. Fuselage (Cross-Flow Separation, Vortex Formation)

- Nose Shape important — ogive-like & sharp
- Cross-Section
  - > ellipse 2:1 & 1:2
  - > chine

> Need LV since probably distort flow

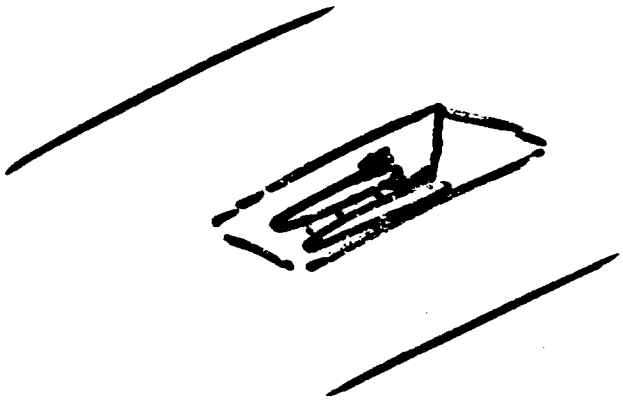
> study Re# effects

> Unsteady effects can be important. laser sheet to characterize. need further unsteady instrum.

6. Inlet Flows

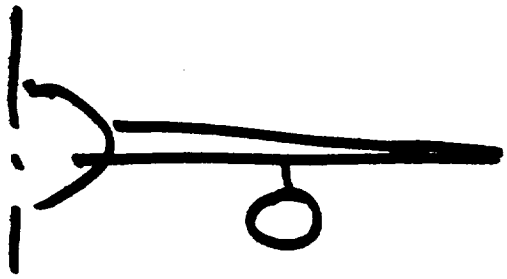
- Covered in part by Exp 5, but need to emphasize for fighters: <u>inlet flow</u> will be very <u>configuration dependent</u>.
- Inlets placed in unique locations where, for example, fuselage vortex can be swallowed by inlet, leading to inefficient engine performance

7. STORE INTEGRATION



- SIMPLE CAVITIES
- STEADY AND UNSTEADY PRESSURES
- FLOW FIELD DIAGNOSTICS
- FLOW VIZ
- SUB, TRANS AND SUPERSONIC

7. STORE INTEGRATION (CONT'D)



- SIMPLE PYLON STORE GEOMETRY
- TIME AVERAGED FLOW FIELD VELOCITIES INCL. WING WAKE
- PRESSURE DISTRIBUTIONS
- FLOW VIZ

DATA DESIRED

LOCAL FLOW EFFECTS - BASIC EXPS.

- SURFACE PRESSURES
- TIME AVERAGED VELOCITY VECTORS, ρ AND T.
- REYNOLDS STRESSES
- FLOW VIZ
- UPSTREAM B.L.

CONFIGURATIONS

- PRESSURE DISTRIBUTIONS
- SKIN FRICTION
- FORCES AND MOMENTS
- FLOW VIZ
  - LASER OR LIGHT SHEET (DYNAMIC)
  - LASER INDUCED FLOURESENCE
  - SURFACE OIL, TUFTS
- UPSTREAM WALL B.L.
- FLOW FIELD DIAGNOSTICS

NEW COMPUTATIONAL, EXPERIMENTAL FACILITY & INSTRUMENTATION NEEDS

- INSTRUMENTS FOR TIME VARYING DATA IN A PLANE OR VOLUME (QUANTITATIVE)

- LINES OF WALL PRESSURE DATA FOR BASIC AND CONFIGURATION EXPERIMENTS

- UPSTREAM WALL B.L. PROFILES — FOUR WALLS

- DOCUMENTED FLOW UNIFORMITY AND FLOW QUALITY

Standard Test Cases

A) [illegible] (Fwd. & Aft sweep)

- [illegible]
- [illegible]
- [illegible]

B) DELTA WING

- 65° DELTA (W.L.E.)
- [illegible] DELTA ([illegible], B.L.E. T.E. Flaps).

C) [illegible] Aft body/Tail/Jet

GROUP D

Internal Flows

Bldg. 245 / Rm. 215

Suggested Spokesperson: B. Lakshminarayana

B. Anderson
S. Connell
R. Delaney
T. Doligalski
C. Forrester
R. Gaugler
F. Gessner
M. Hathaway
H. Mongia
D. Monson*
W. Patrick
~~J. Zion~~

* Guide and room coordinator

R. Boray
L.A. Schutzenhofer
P.K. McCormaughey

INTERNAL FLOW GROUP

- BASIC EXPERIMENTS
- COMPONENT EXPERIMENTS
- SYSTEM EXPERIMENTS
- MEASUREMENT TECHNIQUES
- NEW FACILITIES
- PHENOMENA

PHENOMENA

TRANSITION

TURBULENCE

ROTATION /CURVATURE EFFECTS

MIXING PROCESS

WALL LAYER (2D - 3D)

3D VISCOUS LAYERS

UNSTEADINESS

SHOCK BOUNDARY LAYER INTERACTION

SEPARATION

MICRO GRAVITY EFFECTS

BASIC EXPERIMENTS

1. CURVED DUCT - 3D, VISCOUS, UNSTEADY, SEPARATED, SWIRLING FLOW

2. STRUT - WALL ; 3D, HEAT TRANSFER, SEPARATED, ADVERSE PRESSURE GRADIENT, WAKE MIXING, LOW - HIGH SPEED

3. CONFINED JET MIXING (INCLUDING LOBE MIXING) - INCLUDE ΔV, ΔT, ΔP.

4. 3D STRUT / BL INTERACTION

5. ROTATING DUCT

COMPONENT EXPERIMENTS

(1) FLOW MEASUREMENT AND HEAT TRANSFER IN SINGLE STAGE ROTOR/STATOR

(2) ROTOR/STATOR INTERACTION

(3) HEAT TRANSFER/FLOW MEASUREMENT IN HIGH TEMP TURBINE

(4) FLOW MEASUREMENT IN MULTI STAGE COMPRESSOR

(5) CASCADE FLOWS

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SYSTEM EXPT

1. JET ENGINE
   SUBSONIC / SUPERSONIC
2. PROPULSION INTEGRATION

3D CURVED DUCT VALD. EXP.

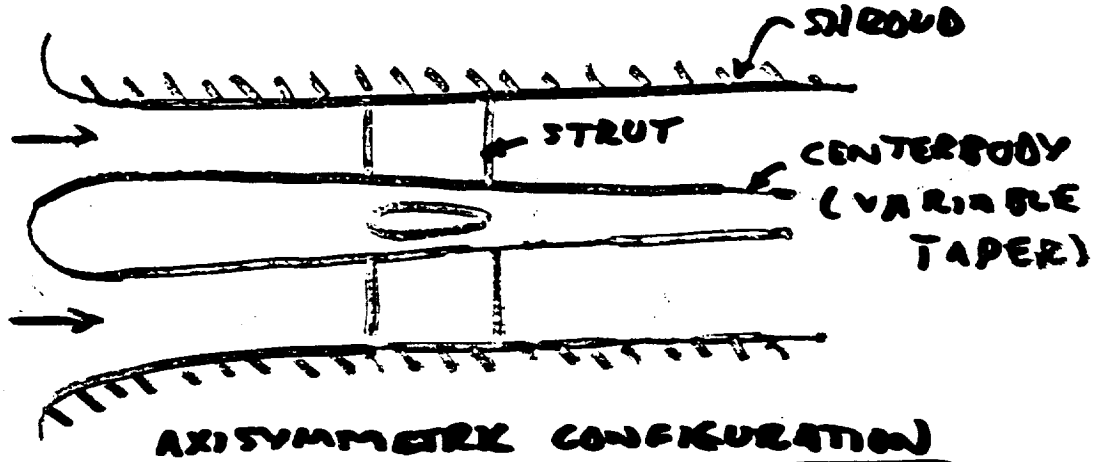
(NASA/UNIV. EFFORT)

- PHENOMENA/ISSUES
  - 3D SEPERATION - STEADY/UNSTEADY
  - EFFECT OF WALL CURVATURE
  - EFFECT OF SWIRL
- GEOMETRY
  - CURVED DIFFUSING DUCTS
    (INPLANE/OUT-OF-PLANE)

- FLOW CONDITIONS

  - LAMINAR/TURBULENT FLOW
  - SWIRLING INLET FLOW
- COMPUTATIONAL ISSUES
  - PARABOLIZED N.S.
  - TIME AVERAGED N.S.
  - TURBULENCE MODELS

STRUT - ENDWALL FLOW



AXISYMMETRIC CONFIGURATION

OPERATING CONDITIONS

1. SUBSONIC INLET MACH NO. (INCOMP. TO COMP)
2. HIGH REYNOLDS NO. FLOW ABOUT STRUT
3. UNHEATED AND HEATED INLET FLOW
4. THIN-TO-THICK BL UPSTREAM OF STRUT
5. UNSEPARATED MAIN FLOW; UNSEPARATED TO LOCALLY SEPARATED FLOW ABOUT STRUT

FLOW VARIABLES (TO BE MEASURED UPSTREAM, AROUND AND DOWNSTREAM OF STRUT IN WAKE REGION)

1. MEAN VELOCITY COMP (3)
2. REYNOLDS STRESS COMP (6) - CONDITIONALLY AND CONTINUOUSLY TIME AVERAGED
3. LOCAL WALL SHEAR STRESS (MAG. & DIR.)
4. LOCAL WALL TEMP. AND HEAT TRANSFER

ROTATING DUCT

SIMULATE FLOW IN
TURBINE AXIAL FLOW
COMP/ CENTRIFUGAL
COMPRESSOR

MEASURE U_i, $\overline{u_i u_j}$
T_0, p, etc.

VARY ROTATION NUMBER,
REYNOLDS NO

3D SHOCK/BOUNDARY LAYER INTERACTION

- Mach number range 3 – 30
- Vortical content influence
- Tripped transition influence
- Bleed influence
- Wall temperature boundary condition
- Heat transfer influence
- Parameters promoting gross unsteadiness
-

ROTOR/STATOR INTERACTIONS

- Flow field surveys
  - velocity, 3D
  - temperature/density/pressure
- Boundary layer
- Surface measurements
  - pressure
  - shear stress
  - heat transfer

steady & unsteady

CASCADE FLOWS.

- BASE FLOWS.
- 3D FLOWS.
- TIP CLEARANCE FLOWS.
- HEAT TRANSFER.
- COOLANT INJECTION.
- 3D SHOCK/BL. INTERACTION.

→ NATIONAL TRANSONIC CASCADE TUNNEL

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SINGLE STAGE TURBINE/COMP.

- 3-D Viscous flows (High speed / low speed)
  end wall flows
  blade boundary layers
  Tip clearance flows
  wake characteristics

- Heat Transfer / High Temperature

MULTI STAGE TURBOMACHINES

- Inter/Intra Blade row measurements

  Velocity

  Pressure

  Temperature

- Blade surface measurements

- End wall

'SYSTEM EXPERIMENTS'

S1) JET ENGINE (INLET TO EXHAUST)

- LEVEL I	FEASIBILITY STUDY	SHORT TERM	
- LEVEL II (CALIBRATION ?)	LIMITED ENVIRON. DEFINITION	MED. TERM	INSTRU ↓
- LEVEL III (VALIDATION ?)	'COMPLETE' ENVIRON. DEFINITION	LONG TERM	ADVANC

S2) PROPULSION / AIR FRAME INTEGRATION STUDIES

- IN FLIGHT VERIFICATION

ADVANCED OPTICAL FLOW MEAS. TECHNIQUES

- Laser Velocimetry
  - 3-D simultaneous
  - State variable (Temp / density)
  - multi-point velocity correlations
  - seeding techniques
- Fiber Optics
  - complex geometries/confined passages
  - rotating frame meas. (optical slip ring)
- Tomography
  - global flow field measurements
- Heat Transfer
- Skin Friction

FACILITY REQUIREMENTS

F1) NATIONAL TRANSONIC CASCADE TUNNEL

- NO CURRENT ACTIVE FAC. IN U.S.
- AVAILABLE IN EUROPE, ETC.
- HIGH & LOW SPEED

F2) HIGH TEMPERATURE HEAT TRANSER COMPRESSION FACILITY

- NOT AVAILABLE IN U.S.
- PILOT FACILITY INITIALLY (LOW COST)
- LARGE SCALE

RECOMMENDATIONS

(1) FUND AT LEAST 2 BASIC AND AT LEAST 2 COMPONENT EXPERIMENTS

(2) ESTABLISH A DATA BANK TO DISSEMINATE THE INFORMATION / DATA

(3) EVERY CFD EXPERIMENT SHOULD HAVE A STRONG NASA / UNIVERSITY, INDUSTRY / NASA, INDUSTRY / UNIVERSITY INTERACTION

(4) ORGANIZE A WORKSHOP TO COMPARE / VALIDATE CFD CODE / EXPERIMENT

(5) ENCOURAGE STRONG INTERACTION BETWEEN CFD / EXPERIMENTALISTS

6 ESTABLISH INTERNAL FLOW FACILITIES; CASCADE; TRANSIENT HEAT TRANSFER FACILITY

7 INITIATE PNSTRUMENTATION (3D LDV - TOMOGRAPHY) PROGRAM FOR INTERNAL FLOW MEASUREMENT

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PRIORITIES - EXPERIMENTAL PROGRAM

1. CURVED DUCT
2. 3D SHOCK / B.LAYER INTERACTION
3. 3D VISCOUS HEAT TRANSFER MEASUREMENT IN SINGLE STAGE COMP / ROTOR
4. ROTOR / STATOR INTERACTION
5. REST LINER / ANNULAR CASCADE
6. STRUT / WALL FLOW FIELD
7. CONFINED JET MIXING
8. MULTI COMPONENT / MULT. PHASE FLOW BODY
9. JET ENGINE FLOW FIELD
10. PROPULSION INTEGRATION

GROUP E

Hypersonics - I

Chemically Reacting External/Internal Flows

Bldg. 245 / Rm. 141

Suggested Spokesperson: G. Deiwert

R. Boray
G. Corpening
~~[illegible]~~
E. Mularz
J. McDaniel
C. Park*
C. Rogers
T. Strawa
~~[illegible]~~

D. Cooper
M. Green
G. Hull
H. Hamilton
L. Lasher

* Guide and room coordinator

HYPERSONICS - I
Chemically Reacting External/Internal Flows

MISSION DRIVERS

AOTV - External Flow

- High Temperature
- Low Density
- Dissociation & Ionization
- Nonequilibrium Radiation

NASP - Internal Flow

- Air Breathing Propulsion
- Hydrogen-Air Combustion
- Turbulent Mixing/Combustion
- Propulsion/Airframe Integration

HYPERSONICS - I
Chemically Reacting External/Internal Flows

Key Efforts for Modeling & Validation

EXTERNAL FLOWS

FLOW PHYSICS / MODEL DEVELOPMENT - Type A/B

- SHOCK TUBE STUDIES
  - Species Distributions
  - Vibrational Nonequilibrium
  - Nonequilibrium Radiation
- COMPUTATIONAL CHEMISTRY
  - High Temperature Reaction Rates
  - and Thermodynamic and Transport Properties
- ALGORITHM DEVELOPMENT
  - Fully Coupled Algorithms
  - Low Density Flows
  - Transport Phenomenon

HYPERSONICS - I
Chemically Reacting External/Internal Flows

Key Efforts for Modeling & Validation

EXTERNAL FLOWS

VALIDATION and CALIBRATION EXPERIMENTS - Type C/D

- BALLISTIC RANGES and SHOCK TUNNELS
  - Shock Shapes over Simple Bodies
  - Density Field over Simple Bodies
  - Surface Heat Flux and Pressure
  - Drag
  - Fully Defined Free Stream Conditions

HYPERSONICS - I
Chemically Reacting External/Internal Flows

Key Efforts for Modeling & Validation

INTERNAL FLOWS

- FLOW PHYSICS and MODEL DEVELOPMENT - Type A/B
  - Time Dependent Data
  - Shear Layer Studies
  - Turbulent Reacting Flows
  - Species Distributions
  - Reaction Rates
  - Thermodynamic and Transport Properties
- VALIDATION and CALIBRATION - Type C/D
  - Direct and Semidirect Connect Combuster/Nozzle Tests

HYPERSONICS - I
Chemically Reacting External/Internal Flows

CRITICAL PROBLEM AREAS

- HEAT TRANSFER
  - Convective
  - Radiative
  - Wall Catalycity
- TRANSPIRATION and ABLATION
- BASE and WAKE FLOWS
- AERODYNAMICS
  - Pitching Moment
  - Drag
  - Stability
- PROPULSION
  - Inlet Boundary Layer
  - Turbulent Combustion/Mixing
  - Nozzle/Plume -- 3 Body recombination

HYPERSONICS - I
Chemically Reacting External/Internal Flows

REQUIRED CAPABILITIES

- DATA BASE
  - Thermodynamic and Transport Properties
  - Chemical Kinetics (Rates)
- COMPUTER FACILITIES
  - Multiple Species Equations - Source Terms
  - Multiple Energy Equations
  - Multiple Time and Length Scales
- INSTRUMENTATION
  - State of the Art and New Developments
    e.g. CARS, LIF, Holography, Planar Imaging, Spectroscopy
  - Impulse Facilities - Short Run Times

HYPERSONICS - I
Chemically Reacting External/Internal Flows

REQUIRED CAPABILITIES

FACILITIES

- REACTIVATE AND UPGRADE EXISTING RESEARCH FACILITIES
  - Shock Tubes
  - Shock Tunnels
  - Ballistic Ranges
  - Expansion Tube
  - Propulsion Facilities
- BUILD NEW RESEARCH FACILITIES
  - Rail Gun / Range
  - High Enthalpy Shock Tube
- REAL GAS (FLIGHT ENTHALPY) FACILITIES
  - Rail Gun and/or Arcjet

SPECIALIZED SKILLED STAFF

HYPERSONICS - I
Chemically Reacting External/Internal Flows

COOPERATIVE/JOINT VENTURES

- NASA Hypersonic Initiative
  - TRAINING
  - NEW ALGORITHME
  - BASIC PHYSICS
  - EXPERIMENTS ??
- AFE (ARC/JSC/LaRC/MSFC)
- SWERVE (NASA/Sandia)
- NASP

HYPERSONICS - I
Chemically Reacting External/Internal Flows

STANDARDIZED TEST CASES

- COMBUSTION/INTERNAL FLOW
  - AFOSR Turbulent Combustion Report
  - Heirarchal Series of Mixing/Combustion Experiments
- EXTERNAL FLOW
  - Shock Shapes on Simple Bodies
  - Density Field over Simple Shapes
  - Surface Heat Transfer and Pressure
  - Shock Structure

GROUP F

Hypersonics II

External Aerothermodynamics

Bldg. 245 / Rm. auditorium

Suggested Spokesperson: S. Bogdonoff

I. Bhateley
R. Conti
G. Chapman
D. Chaussee
D. Dwoyer
J. Grace
H. Hamilton
C. Horstman
W. Lockman*
R. Lowe
R. Newman
P. Rodi
G. Settles
F. Spaid
E. Vas
A. WIETING

* Guide and room coordinator

Hypersonics II

External Aero-thermodynamics

Defined range $M \sim 6$ to hypervelocity

Problem Definition

I Boundary Layer Effects

- Compressibility — transformation
- Wall Wake Law
- Turbulence model / physics
- S.L. - Stability & mixing

II Wall Effects

- Cooling
- roughness
- Catalysis
- Mass addition
  - Transpiration
  - ablation

III B.L./S.L. Characteristics
- Laminar
- transitional / relaminarization
- turbulent
- gradient effects
  - entropy
  - P
  - T
  - Shock waves
- Separation / reattachment

IV Real Gases
- Equilibrium
- Non-Equil.
- Frozen
- Gas properties
- Radiation

V Low Density
- Boundary of Continuum
  - M, geom., alt.
- Nose / L.E. effects
- Translational flow model.

Priorities

A. B.L. Characteristics
- transition
- physics of turbulence

B. Real Gases
- Chemical Kinetics
- Chem / turbulence interaction
- Gas properties
- Radiation

C. Low Density
- boundary definition
- transitional model

Facilities and Experiments
- physical and Computation -

A. A B.L. facility to check laminar stability theory as an approach to transition - study the physics of turbulence.

Develope laminar, natural transition, fully turbulent flows - base line
Disturb laminar flow - observe!

Instrumentation:- full mean flow and wall charac. Instantaneous meas to resolve stability analysis -

Facility would provide ability to evaluate conditions which influence transition

- Facility scale adequate to get resolution and full B.L. conditions

new M (6-9) Perfect gas - can do now. BUT requires flow conditioning for transition. Must validate!

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Flight test required for overall charac.

High M. Problems of enthalpy - real gas. BUT needed to complete study.

B. Facilities to study Rate equations and models
- Can do with shock tubes

Facilities to study catalysis, real gases, Hypervelocity, transition.
- Within capability of LARGE range. Model 1-2 ft. on board instrumentation and ground based instruments

Facilities to study chem/turbulence interaction
- Start with heat addition to perfect gas - "A"
need follow on - extended "A"

C. Facilities to generate high M flows - Continuum to FM.

- Can do with present Capability and Instrumentation
  - Hot - Shock tunnels
  - Cold - Continuous tunnels
  - Free jets

  (no flow conditioning problem as in "A")

- Calc. N.S. FM - overlap
  models - geometry
  nose / L.E. effects

Issues

1. Priority list. -
   Can start low M now
2. All problems on Priority list at High M are Critical.
3. Noted in section on facilities
4. All projects probably require coop / joint venures.
5. Noted in facilities section -