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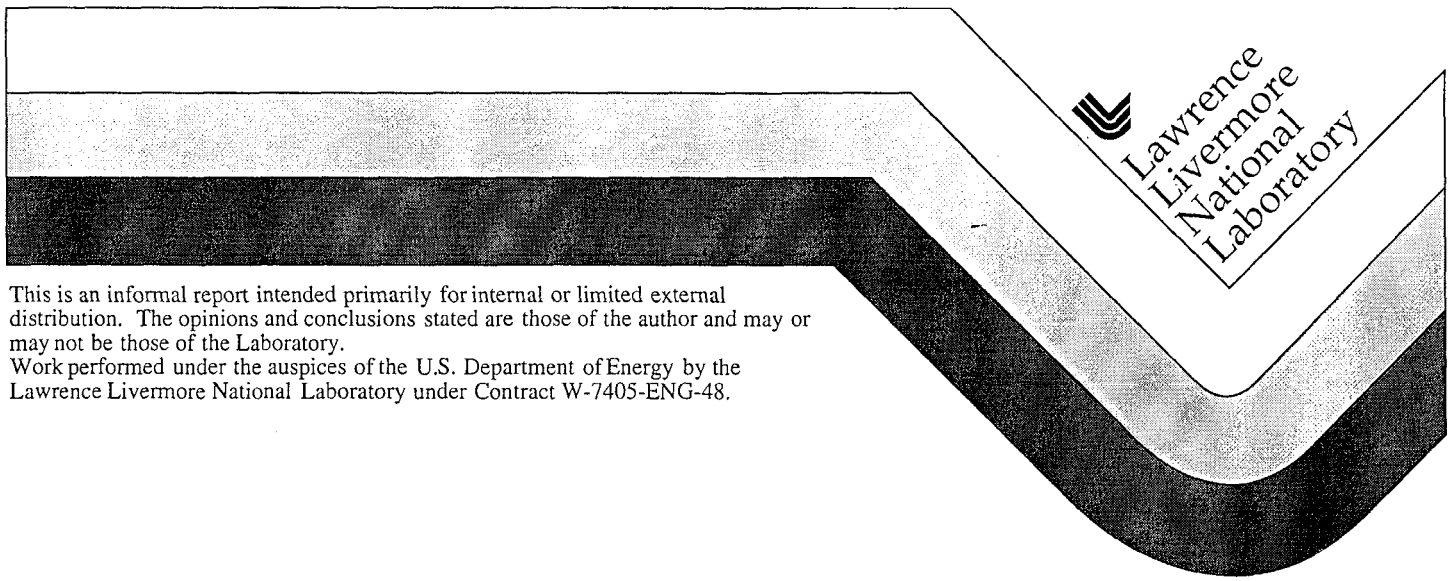
March 1999 Working Group Meeting on Heavy Vehicle Aerodynamic Drag: Presentations and Summary of Comments and Conclusions

Rose McCallen
Kambiz Salari
Fred Browand
Mark Brady
Jim Ross

March 1999



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March 1999
Working Group Meeting on
Heavy Vehicle Aerodynamic Drag:

Presentations and Summary of Comments and Conclusions

Jointly written by

Lawrence Livermore National Laboratory
Sandia National Laboratories
University of Southern California
California Institute of Technology
NASA Ames Research Center

Introduction

A Working Group Meeting on Heavy Vehicle Aerodynamic Drag was held at Lawrence Livermore National Laboratory, Livermore, California on March 11, 1999. The purpose of the meeting was to present technical details on the experimental and computational plans and approaches and provide an update on progress in obtaining experimental results, model developments, and simulations. The focus of the meeting was a review of the experimental results for the integrated tractor-trailer benchmark geometry called the Sandia Model in the NASA Ames 7 ft x 10 ft wind tunnel. The present and projected budget and funding situation was also discussed.

Presentations were given by representatives from the Department of Energy (DOE) Office of Transportation Technology Office of Heavy Vehicle Technology (OHVT), Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratories (SNL), University of Southern California (USC), California Institute of Technology (Caltech), and NASA Ames Research Center.

This report contains the technical presentations (viewgraphs) delivered at the Meeting, briefly summarizes the comments and conclusions, and outlines the future action items.

Overview of the Project, Current Funding, and Future Workshop

An overview of the project was presented by Rose McCallen of LLNL. The viewgraphs are enclosed. Budget issues were presented as well as the project calendar of events and milestones.

It was emphasized that the program deliverables are being met only because of the team's success in leveraging funds from internal research support (e.g., LDRD and Tech Base at the National Labs) and the support of other agencies (e.g., DOD, Caltrans, NSF, ASCI) for related work. It was noted that the current budget does not provide funds for the Fall 99 Workshop. LLNL has set aside some of its funding so that we can make commitments to a location and date. Pending SAE approval, the Workshop will be scheduled in conjunction with the SAE Truck and Bus Conference, Detroit, Michigan in November 1999.

Richard Wares of DOE OHVT emphasized the importance of industries positive support for this project. It is also important for the team to keep DOE informed of the past, present, and future significant deliverables, identifying our success in using leveraged funds to achieve these accomplishments, as we have done.

NASA's 7-ft x 10-ft Wind Tunnel Tests

Jim Ross of NASA Ames presented (with viewgraphs and in computer animation format) our first look at the experimental data on the Sandia Model (a 1/8 scale model) in the 7 ft x 10 ft wind tunnel. In fact, the tests at NASA were still underway on the date of the Meeting. The tests were started on February 12th and were expected to continue through March 12, 1999. The purpose of the tests are for validation of the computational fluid dynamics (CFD) models and for further insight into truck flow phenomena. The viewgraph presentation is enclosed.

The tests were lead by Bruce Storms who was responsible for the preliminary data reduction presented at the Meeting. In addition to drag and discrete and unsteady pressure measurements, an entire suite of new and innovative measurement techniques were used. The NASA Instrumentation Group members that successfully executed these tests and their accomplishments are summarized below.

J.T. Heineck and Stephen Walker of NASA Ames gathered particle image velocimetry (PIV) measurements. The PIV measurements were taken in the model wake, providing the three components of velocity in the plane of a laser sheet. This was only the second time that the 3 simultaneous velocity components have been measured successfully using PIV in a production wind tunnel. (The first was made by the NASA Ames team in July of 1998.) PIV data was taken for Reynolds number (Re) of 0.5 million and 2 million based on the trailer width and upstream velocity. In all, more than fifty data sets were collected. (A sample of the PIV results were presented as an animation and not included in the attached viewgraph presentation.)

NASA's Dave Driver used his state-of-the-art oil film interferometry techniques (OFI) for measuring skin friction and NASA's James Bell performed pressure sensitive paint (PSP) measurements. The OFI technique can supply quantitative time-averaged skin friction measurements in the body wake (on floor) and the PSP measurements provide time-averaged pressures on the body.

Skin friction measurements on the model body were also provided by Taos hot-film system which can detect flow separation, reattachment, and transition. The Taos System scientists provided the sensors, data collection system, and will be performing the data reduction. A total of 60 data positions were used for the hot-film system (see photograph in attached viewgraph presentation).

Continuum Dynamics also provided (free of charge) boattail plates made to fit our model (see photo in presentation). Tests were conducted with and without the boattail plates. The plates produced a 20% reduction in drag for the model (see plot of drag coefficient versus yaw angle in presentation). A 10% reduction has been measured on a full size truck at similar speeds.

Several issues or important points were raised during the presentation and during the wrap-up discussions later in the day. These are summarized below.

- The drag data for negative yaw was contaminated due to a damaged lever train, but the positive yaw measurements should be correct and adequate (see drag repeatability plot in presentation).
- The PSP data was noisy, but usable (see scatter plot in presentation).
- All other data looks good.
- The PSP downstream camera caused a drag reduction of 4% because of the change in back pressure.
- Several of the NASA wind tunnel measurements do not agree with those performed at Texas A&M on the same model (see comparison of drag measurements in presentation). Data corrections made my Texas A&M are being investigated. The goal is to account for differences and document them.
- The measured inlet profile (see viewgraphs) is measured at the test section entrance for an empty tunnel. Since the front of the model is only about 6 inches from the start of the test section, the inlet profile for the CFD simulations will need to be extrapolated upstream to obtain accurate flow blockage predictions with the model.
- NASA needs to know what format to use in when providing data to the team (e.g., ascii, TechPlot).

Plans for 12' Wind Tunnel Tests

Jim Ross of NASA Ames presented the motivation and some approach ideas for the 12-ft wind tunnel tests to be conducted in FY00 at NASA Ames. Jim also led a discussion on possibilities for the model choice and flow conditions during the wrap-up discussion at the

end of the day.

The 12-ft wind tunnel tests are scheduled for February 2000. The purpose of the tests is to examine Re effects up to full-scale on a 1/8 scale model. The truck industry is very interested in these tests because they recognize that there are discrepancies between the Re effects experienced with a full-size truck and that predicted by experiment on scaled down models in wind tunnels. The NASA test will investigate the minimum Re that can be used in a wind tunnel for accurately predicting the drag effects due to various aspects of the geometry. Geometry aspects that might be considered are the gap distance between the tractor and trailer, the underhood cooling flow, the mirror design, boattail plates, and methods of base drag reduction.

With NASA's ability to acquire detailed unsteady data, these tests serve the dual purpose of being very useful for code validation. However, the CFD team members would then prefer that a simplified body geometry be investigated rather than a more realistic, detailed truck model. It is also anticipated that this data will be used by industry to compare to the simulations generated with commercial tools and a simplified geometry may also be preferred. However, industry would also like to see data for the detailed model for further understanding of the flow phenomena with realistic truck features. No clear direction was established at the Meeting and further discussion is needed.

USC's Wind Tunnel Tests

Fred Browand and Mustapha Hammache of USC presented a review of recent, relevant publications, an update on preparation of their facility for truck model testing, and results of recent digital particle image velocimetry (DPIV) measurements. The viewgraph presentation is enclosed.

Fred Browand presented a review of a recent publication on a hybrid Reynolds averaged Navier Stokes (RANS) and large-eddy simulation (LES) approach called detached-eddy simulation (DES) for simulating turbulent flow like that for trucks (see viewgraphs for paper references). DES appears to be promising for large flow simulations at high Re.

Fred also sited references that discuss some general shape guidance for drag reduction and provides insight into what should be expected with the Sandia Body. For example, separation at sharp front edges has a dramatic effect on drag. Fred has found that the Sandia body exhibits separation from the front round corners at low Re (per USC's test results) and thus, experiences an increase in drag, where at higher Re (as in the NASA tests), the drag can actually be reduced. Another publication provided a relationship between forebody drag and base pressure coefficient. This type of relationship could make it possible to draw conclusions on the full-body drag for a tractor and trailer from measurements or simulations of just the cab drag.

Experimental drag measurements for the Sandia Body (a 1/15 scale model) were presented for the tractor/trailer combination with and without a gap. The purpose of the tests are for validation of the CFD models and for further insight into truck flow phenomena. The recent experiments have investigated Re effects on full-body drag as well as the effect

of separation from the cab corner on full-body drag.

Mustapha Hammache described his DPIV methods, emphasizing the importance of small-scale resolution and maximizing accuracy by reducing the field of observation to achieve higher data resolution. He also presented some recent investigations of vehicle platooning which are relative to our investigation of the flow effects due to tractor/trailer gaps. For platooning, decreasing gap distances causes flow entrainment from the top resulting in increased drag on the forward vehicle, while reducing the drag on the aft vehicle.

Mustapha also spent two weeks at NASA working with J.T. Heineck and others in setup and acquiring the PIV data in the 7-ft x 10-ft wind tunnel.

Computational Model Development and Simulations

An overview of the Reynolds-averaged Navier Stokes (RANS) computation being performed by SNL was presented by Kambiz Salari. Current efforts involve the modeling of an experiment performed on the Sandia Model in the Texas A&M 7-ft x 10-ft wind tunnel during 1995. These RANS simulations include part of the converging section, test section, and part of the expansion region of the tunnel. The tunnel walls are treated as slip boundaries (no penetration). The computational meshes for the RANS simulations range from a coarse mesh of 0.5 million nodes to a medium mesh of 4 million nodes for Re of 1.6 million at 0 and 10 degree yaws. Work has begun on a fine mesh case of 32 million nodes which should improve the ability to capture areas of recirculation and separation on the tractor-trailer. For these calculations an implicit finite-volume compressible flow solver with a one-equation Spalart-Allmaras turbulence model was used. The steady solutions were obtained on a massively parallel machine using 107 and 246 processors for the coarse and medium mesh, respectively. The fine mesh calculation which is under way is using 1414 processors. These solutions will then be used as the initial conditions for a time-accurate RANS calculations.

The large-eddy simulation (LES) approach being used by LLNL was presented by Rose McCallen. This advanced modeling approach is being considered to achieve more accurate simulations with minimum empiricism and thus, reduce experimentation. The flow around a tractor/trailer is time dependent, three-dimensional with a wide range of scales (i.e., the largest scale is on the order of the tuck length and the small scales are smaller than the diameter of a grab handle). The approach and development challenges were presented along with a progress update. LLNL is utilizing an established finite element method where a pressure Poisson equation is solved. (The code development work is funded by LLNL Tech Base funds.) Matrix characteristics and solver implementation issues in a parallel solution environment were discussed. A finite element solver interface (FEI) developed by SNL will be utilized which will provide many state-of-the-art solver options being developed at both SNL and LLNL. Rose also showed a preliminary mesh that demonstrated the benefits of the unstructured grid option.

An LES approach with vortex methods being used by Caltech was presented by Mark Brady. Mark emphasized that this is truly a gridless method (except for the 2D grid on the vehicle surface). Gridless methods appear to be of particular interest to industry, because

of the excess amount of time that is usually spent on mesh generation compared to the simulation run time. In addition, with vortex methods, computations are only performed where nonzero vorticity is present (e.g., near body and in wake) thus, reducing computational effort. Mark discussed other developments that reduce the effective operations from an order of N^2 to order N, where N is the number of computational elements (i.e., vortex packets) which move with the fluid. Mark provided an update on their progress and planned future work. The fast algorithms have been implemented and an advanced LES approach has been developed and will be implemented. Generation of surface grids for complex geometries needs to be implemented and is being worked on for solution of the Sandia Body.

The Multi-Year Program Plan

Part of the afternoon discussion was on the multi-year program plan (MYPP). It is anticipated that DOE will need any modifications or additions made to the MYPP prior to the Program review in April.

One suggestion of interest was the expansion of the MYPP to include thermal management (e.g., underhood flow and cooling flows) as well as aerodynamic management with an analysis approach, not a design approach. The thermal and aero management are coupled. For example, the underhood flow can have a significant effect on the body drag. With this addition, the MYPP could include a more thorough system integration analysis. It is believed that industry would welcome this addition.

Another possibility for expansion of the MYPP would be to investigate active control devices to reduce drag or to provide additional download for braking. Such devices might include Stratford shaping, and/or the addition of oscillatory momentum inputs.

These modifications to the existing MYPP would require some further discussion and it was not reasonable to believe that it could be included by the April 99 deadline.

Future Meetings

The team has been invited to present a paper at the SAE Government/Industry Meeting on April 26-28, 1999 in Washington, DC. Plans are for Rose McCallen to present a brief project overview and Jim Ross will present the wind tunnel test data.

The next Working Group Meeting will take place at USC and will again focus on the NASA 7 ft x 10 ft wind tunnel tests and USC's experimental effort. This will be held in mid July and hosted by USC. Progress updates on the computational effort will also be presented and discussed at the meeting, as well as a continued discussion on the addition of a thermal management effort to the existing MYPP.

Action Items

The follow-on prioritized action items with the individuals responsible for the tasks are as

follows:

1. Complete 7-ft x 10-ft wind tunnel tests, reduce data and analyze, assemble a data report, and distribute data for validation work. (Jim Ross and the NASA Ames experimental team).

2. Provide NASA with the desired data format (ascii or TechPlot). (R. McCallen and K. Salari)

3. Finalize scheduling of Fall 99 Workshop with the SAE Truck and Bus Conference. (R. McCallen)

4. Determine poster and paper presentation options at SAE Truck and Bus Conference. (R. McCallen)

5. Keep Frank Tokarz informed of the past, present, and future significant deliverables, identifying our success in using leveraged funds so that he can adequately represent us at DOE meetings (e.g., OHVT Annual Program Review and Planning Meeting in April). (R. McCallen)

6. Provide DOE with updated budget request by end of March. (R.McCallen)

7. Setup a series of e-mail and conference call discussions in an attempt to determine the pros and cons of the various geometry options for the NASA 12-ft wind tunnel tests currently scheduled for February 2000. (R. McCallen)

8. Try again to setup site visit at Paccar. (R. McCallen)

9. Plan and host next Working Group Meeting at USC. Provide team with agenda at least one week in advance. (Fred Browand and Mustapha Hammache)

Truck Aero Team Meeting

NASA Ames, CA

March 11, 1999

Attendee List

Attendee	Organization	e-mail address
Salvador Aceves	LLNL	acevessaborio1@llnl.gov
Mark Brady	Caltech	mbrady@caltech.edu
Fred Browand	USC	brownad@spock.usc.edu
Richard Couch	LLNL	couch1@llnl.gov
Mustapha Hammache	USC	hammache@spock.usc.edu
Barbara Kornblum	LLNL	kornblum1@llnl.gov
Satish Kulkarni	LLNL	kulkarni1@llnl.gov
Helen Magann	LLNL	magann2@llnl.gov
Rose McCallen	LLNL	mccallen1@llnl.gov
Erma Paddack	LLNL	paddack1@llnl.gov
Jim Ross	NASA Ames	jcross@mail.arc.nasa.gov
Kambiz Salari	SNL	ksalari@sandia.gov
Frank Tokarz	LLNL	tokarz1@llnl.gov
Richard Wares	DOE	richard.wares@ee.doe.gov

- Agenda -

Truck Aero Team Meeting

NASA Ames, CA

March 11, 1999

Purpose of Meeting

Technical details on experimental and computational plans and approaches

Update on progress - experimental results, model developments, simulations

Introduction

Introduction	R. McCallen, LLNL

Experimental Work and Progress

NASA 7'x10' Wind Tunnel Test Results and Plans for 12' Wind Tunnel Tests	Jim Ross, NASA Ames
Wind Tunnel Tests at USC	Fred Browand and Mustapha Hammache, USC

DOE Report

Update	Richard Wares, DOE

Computational Work and Progress

RANS/LES Modeling Progress and Results at SNL	Kambiz Salari, SNL
FEM /LES Development and Modeling Progress at LLNL	Rose McCallen, LLNL
Vortex Method/LES Development and Modeling Progress at Caltech	Mark Brady, Caltech

Wrap-up Discussion

Discussion on Experiments

Discussion on Computations

Calendar of Near Term Events

Near Term Action Items

Date and Location for Next Meeting

Department of Energy

Aerodynamic Design of Heavy Vehicles

Overview of Project

Rose McCallen, Ph.D.

Lawrence Livermore National Laboratory, Livermore, CA

March 1999

University of California Lawrence Livermore National Laboratory

Sandia National Laboratories

USC UNIVERSITY OF SOUTHERN CALIFORNIA

Caltech California Institute of Technology

National Aeronautics & Space Administration

The truck industry relies on wind tunnel and field experiments for aerodynamic design and analysis.

Wind Tunnel Testing

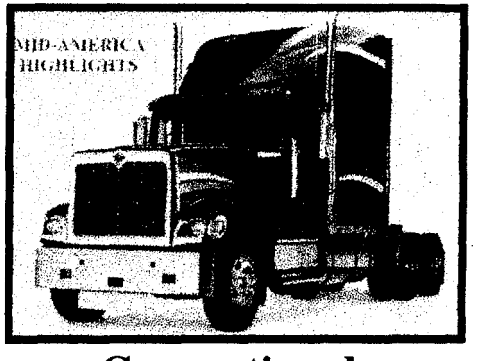
Costly detailed models

Testing is expensive

Trial-error approach to determine drag effects due to

- **general tractor shape, under-body and underhood flow**
- **positioning and shaping of head lamps or turning lights**
- **mirror and grab handle configurations and positioning**
- **tractor-trailer gaps and height mismatch**

Cabover Engine



Conventional

Field Testing

Performed by both manufacturer and fleet operators

Issues

A tractor is paired with several different trailers

Almost no aero design interaction between tractor and trailer manufacturers

The effects of design changes on drag are not well understood and computational guidance is needed and welcomed by industry

The MYPP is based on industry needs and consideration of current technology, funding, and DOE interests.

DOE and National Laboratory interest

- **Reduce heavy vehicle drag -> reduce fuel consumption and emissions**
- **R&D for DOE programs**

Industry needs

- **Advanced computational tools and experimental methods**
  - **Understand the effects of design changes**
  - **Simulate fully-integrated tractor-trailers**
- **Design improvements for drag reduction**

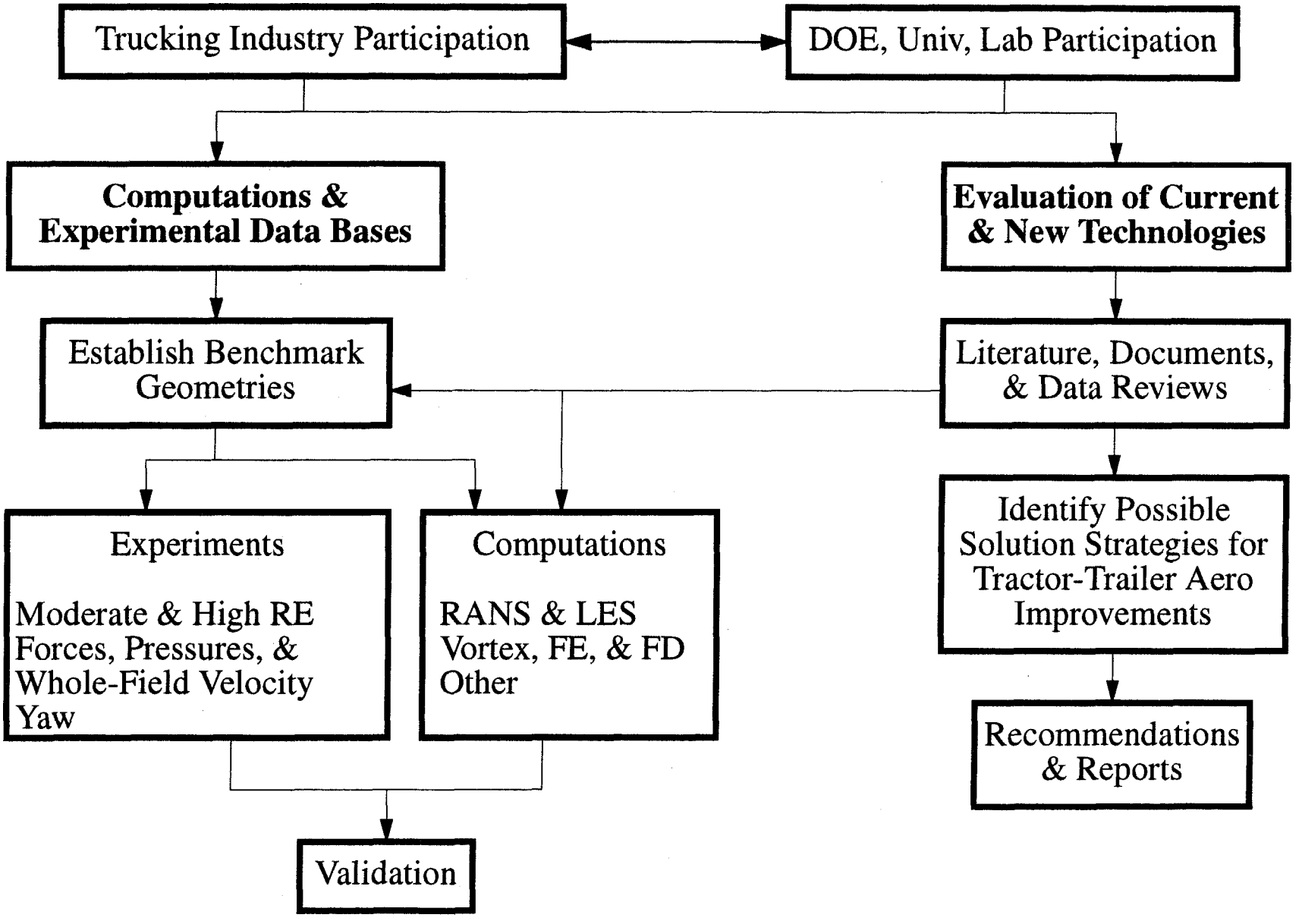
Current technology - CFD is hard!

- **Reynolds-averaged Navier Stokes (RANS) is common approach**
- **Large-eddy simulation (LES) is in development**
- **DPIV measurements can provide full velocity field measurements**

Funding is minimal and we need a plan with a 'near-term impact'

- **FY99: $435K (= 67% of requested $635K)**

The MYPP focuses on development and demonstration of a simulation capability.



Each organization's contributions are critical to the project's success.

Computational Modeling

Rose McCallen (PI)

University of California Lawrence Livermore National Laboratory

Large-Eddy Simulation using Finite Element Methods

Anthony Leonard
Mark Brady

Caltech California Institute of Technology

Large-Eddy Simulation using Vortex Methods

Kambiz Salari
Walt Rutledge
Don McBride

Sandia National Laboratories

Reynolds-Averaged Modeling using Finite Difference Methods

Experimental Modeling

Don McBride
Walt Rutledge

Sandia National Laboratories

GTS Experiments at Texas A&M

Fred Browand
Mustapha Hammache

USC UNIVERSITY OF SOUTHERN CALIFORNIA

Moderate Speed Experiments in Wind Tunnel

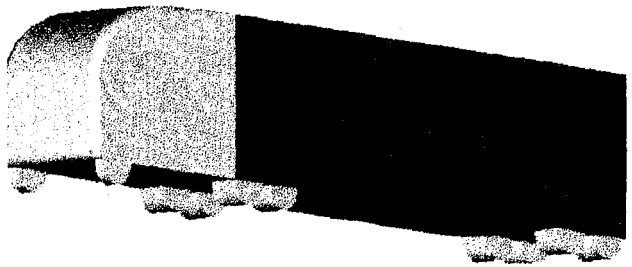
Jim Ross
Bruce Storms, JT Heineck

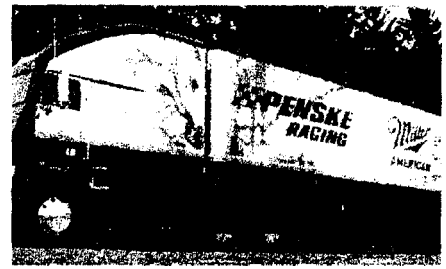
National Aeronautics & Space Administration

High Speed Experiments in 7'x10' and 12' Wind Tunnels

Near-Term Impact: Comparison of RANS and LES and detailed experimental verification for a truck problem.

Sandia's Model

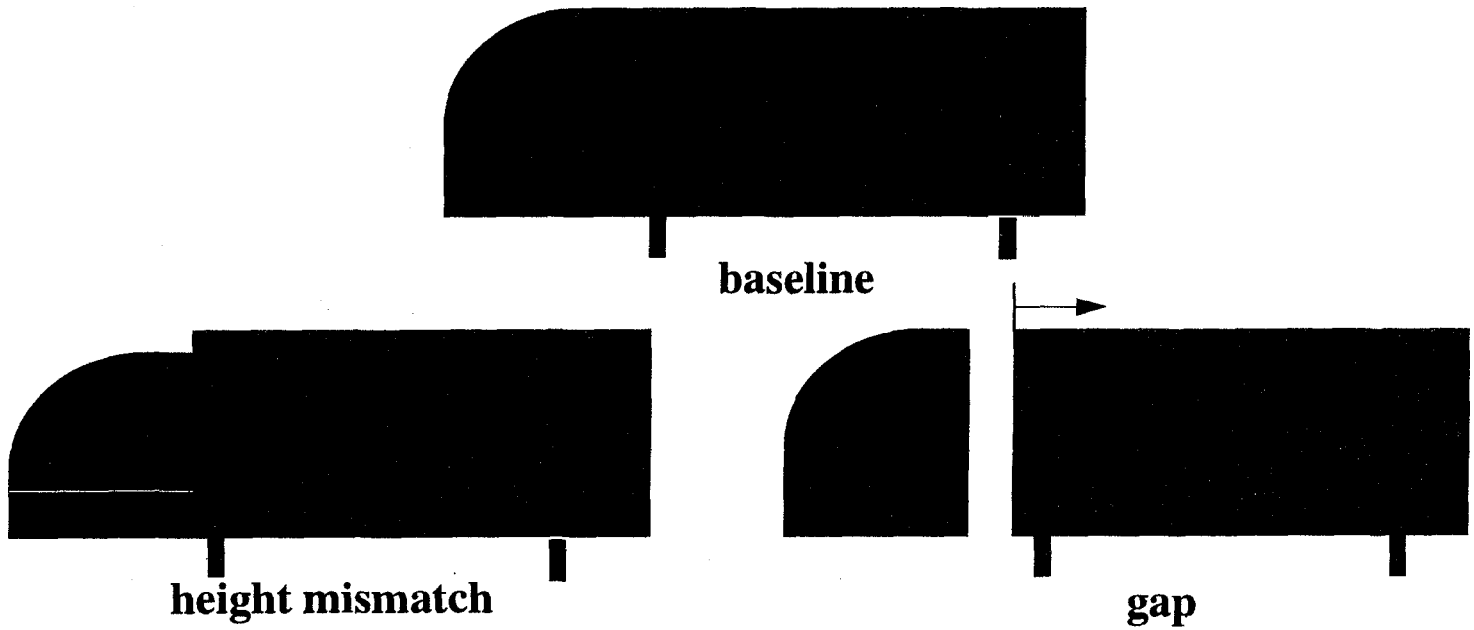




Advantages

Simple geometry with some existing data and some modeling already done

The final detail results will be available for comparison to commercial CFD tools



Our near-term tasks have been identified and prioritized.

Benchmarks

1. Sandia Body

Experiments

- **Texas A&M, Re = 1,600,000 (1:8 scale)**
- **NASA 7'x10', Re = 2,000,000 to lowest Re (1:8 scale)**
- **USC wind tunnel, 200,000 < Re < 400,000 (1:15 scale)**

  With/without height mismatch and gap

Computations

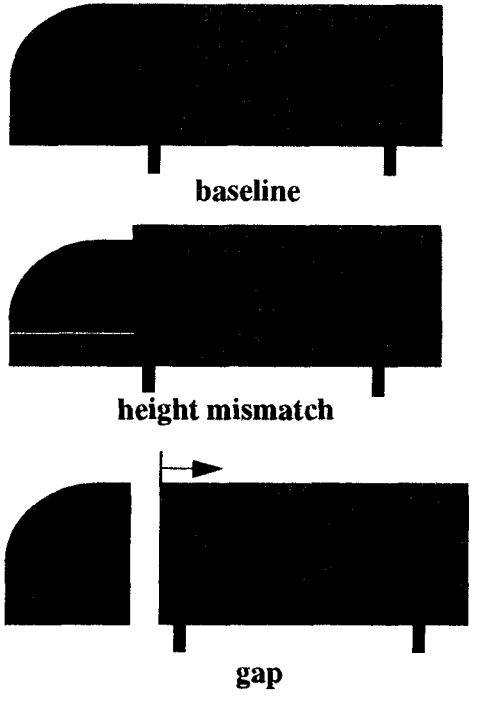
- **RANS for high and low Re (SNL)**
- **LES for low Re, attempt at high Re (LLNL and Caltech)**

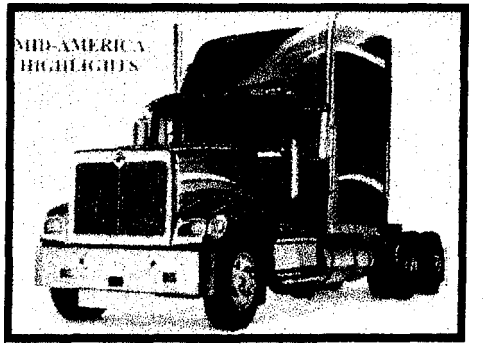
2. New Model Design (USC)

3. Navistar's Model for Re sensitivity study

- **NASA 12' wind tunnel**

  Re_{max} = 5,000,000, model with/without components





Our budget is not consistent with projected funding.

	Computations & Experiments	Evaluation of Current & New Technologies	Final Report	Total requested/ Year	Total received/ Year
FY98	$276K	$34K		$310K	$325K
FY99	$630K	$5K		**$635K**	**$435K**
FY00	$1,045K	$188K		$1,233K	
FY01	$1,095K	$188K		$1,283K	
FY02	$855K	$161K		$1016K	
FY03	$818K	$161K		$979K	
FY04	$120K	$124K	$34K	$278K	
TOTAL				$5,734K	

Funding for FY98 and FY99

	FY 98	FY 99
LLNL	**$100K**	**$170K***
SNL	**$100K**	**$80K**
USC	**$50K**	**$80K**
Caltech	**$50K**	**$80K**
NASA	**$25K**	**$25K ($6K)**
Totals	**$325K**	**$435K ($441)**

* Includes project management tasks, LES modeling, and $15K for workshop.

It was necessary to leverage other funding sources.

SNL	**- past data obtained at Texas A&M**	**Free**
	- loan of model to NASA	**Free**
	- LES R&D	**LDRD**
	- computational resources	**ASCI**
USC	**- instrumentation**	**Caltrans, NSF**
Caltech	**- LES model development**	**ASCI, DOD**
	- computational resources	**ASCI, NSF, DOD**
NASA Ames	**- 7'x10' wind tunnel tests**	**Free**
	- 12' wind tunnel tests	**1/3 Cost**
	- loan of Navistar's model	**Free**
LLNL	**- computational resources**	**ASCI**
	- LES and code development	**ASCI/Tech Base**

The projected milestones are segregated into benchmark cases with advancing levels of complexity.

Projected milestones for first four years of project (FY98 through FY01)

Task	Milestone
Workshop II	2/98
MYPP with projected budget and milestones	5/98
Continued site visits / Working Group Meetings (reports)	8/98, 10/98, 3/99
Level 1 Benchmarks: Establish generic shapes and outline test cases for investigation of trailer-tractor height and gap mismatch	9/98
Level 2 Benchmarks: Establish generic shapes	9/99
Test data at moderate Re for Level 1 benchmarks	11/99
Test data at high Re for Level 1 benchmarks	11/99
Workshop III	11/99
RANS, LES/FEM, LES/Vortex computations of Level 1 benchmarks at moderate Re	12/99
RANS, LES/FEM, LES/Vortex computations of Level 1 benchmarks at high Re	12/00
Test data at moderate and high Re for Level 2 benchmarks	9/01

We have a full calendar over the next 8 months.

Web Page (3/99)

- **Maintain with current information, links, etc.**

Progress Report (4/99)

- **Each organizations input needed**

SAE Meeting, Washington, DC (4/99)

- **Abstract submitted**
- **Need computational/experimental results to present**

MYPP (5/99)

- **Submit updated/final version to DOE (Put design/integration task back in? Edits?)**

Working Group Meeting (6/99)

- **USC/Caltech visit**

Progress Report (7/99)

Workshop III, Detroit, MI(11/99)

- **Defined purpose, agenda, dates, etc.**
- **Waiting for SAE approval**
- **Determine invited speaker, advertise, prepare presentations, etc.**

GTS Model Experiment in the 7x10

Bruce Storms

J.T. Heineck

Steve Walker

James Bell

Dave Driver

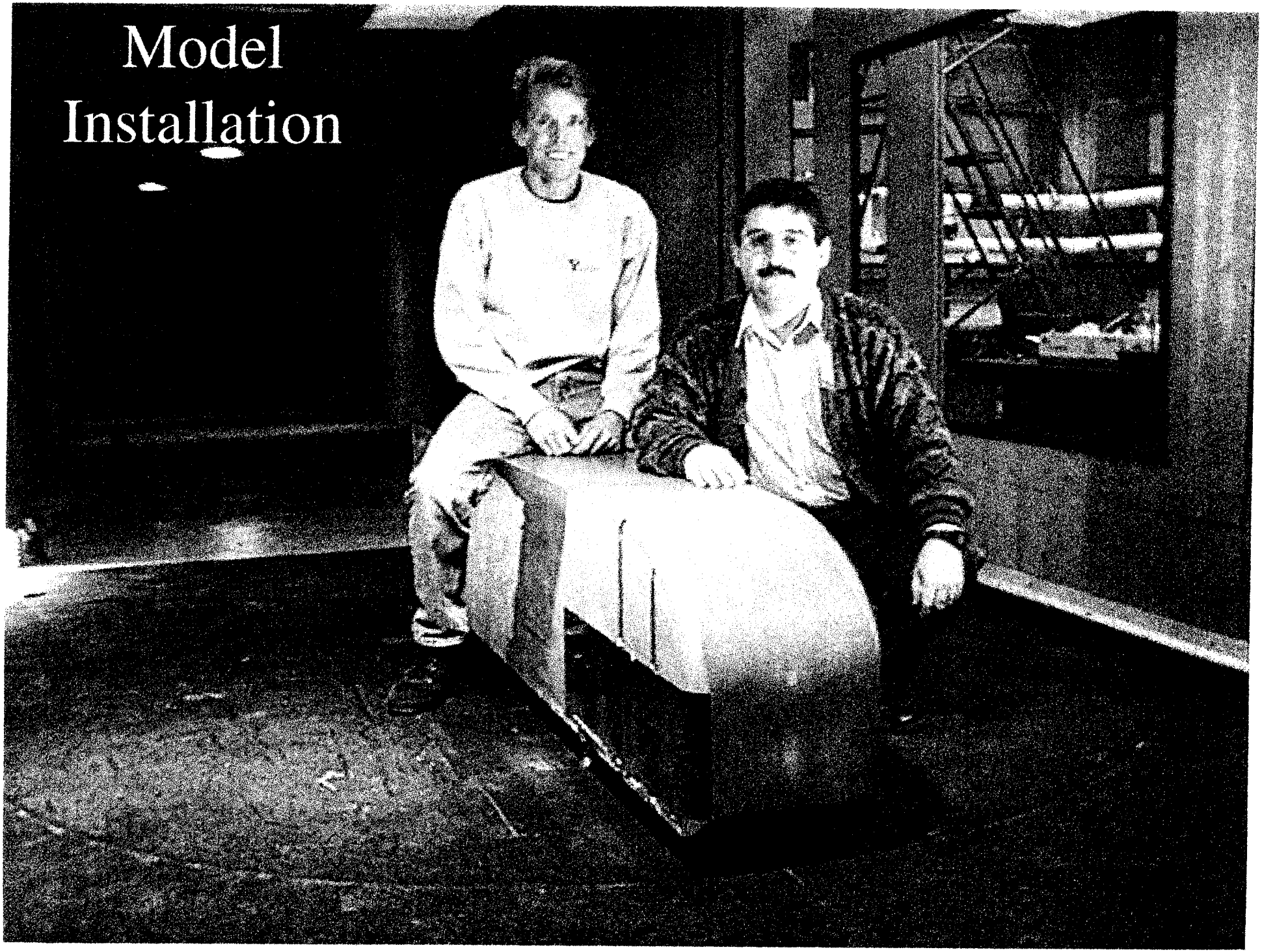
etc...

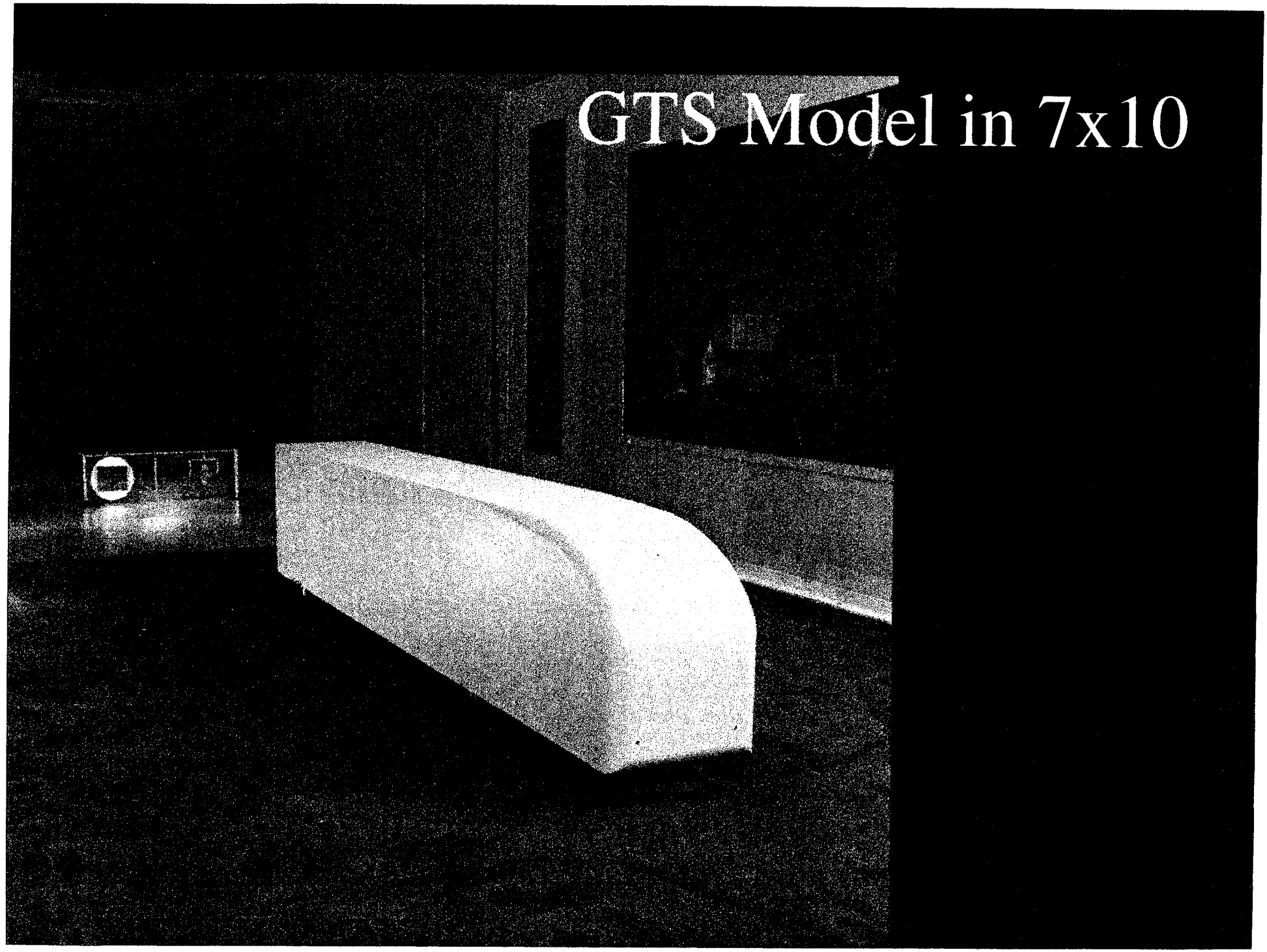
Test Summary

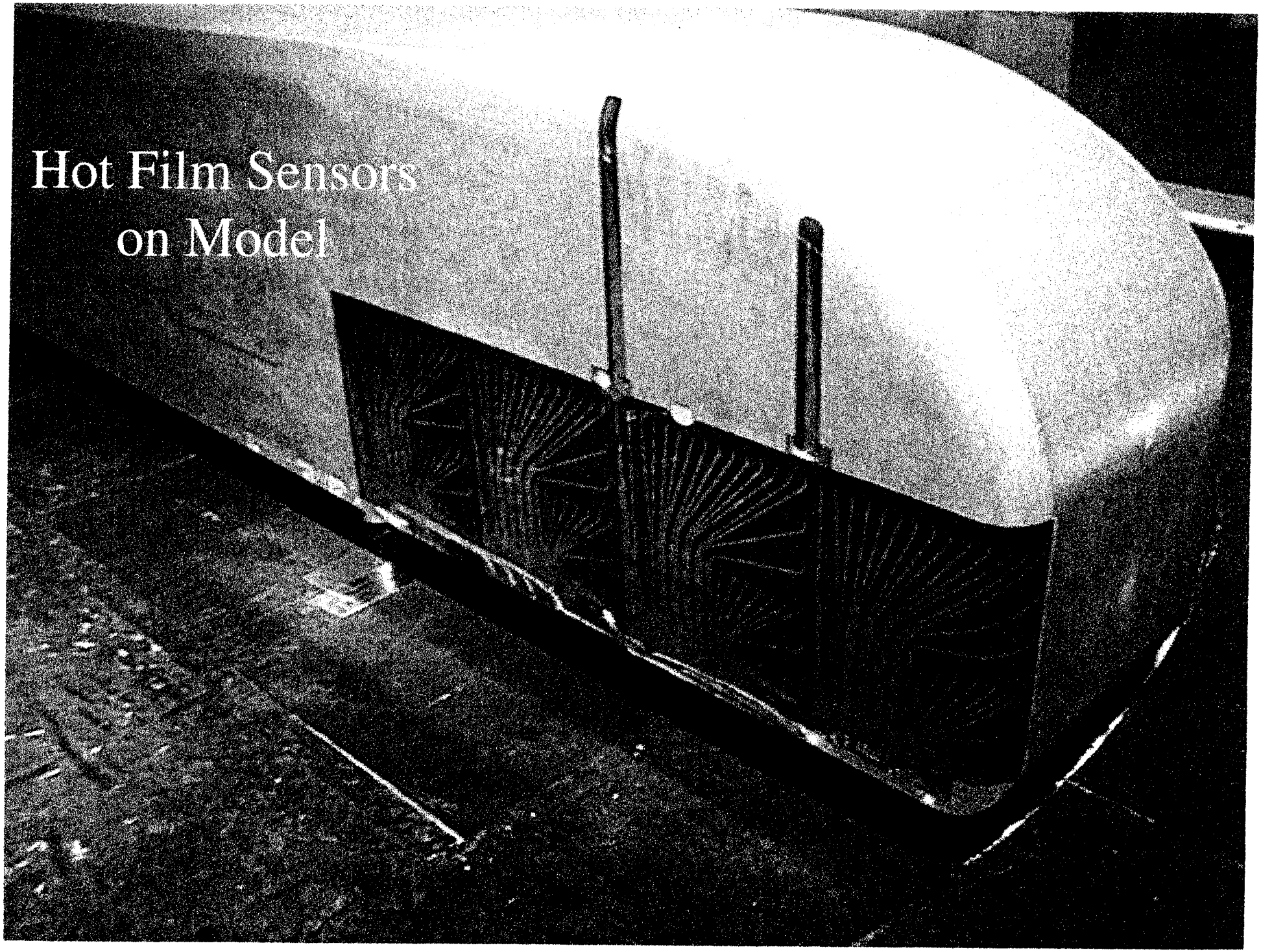
- Test started February 8
- Test complete March 12
- Objective - CFD validation
- Principle measurements
  - Drag and discrete pressure measurements
  - Pressure-Sensitive Paint (PSP)
  - Unsteady pressure (one point on rear "door")
  - Skin friction (oil film interferometry)
  - Particle Imaging Velocimetry
  - Transition (surface hot films)

Summary of Results

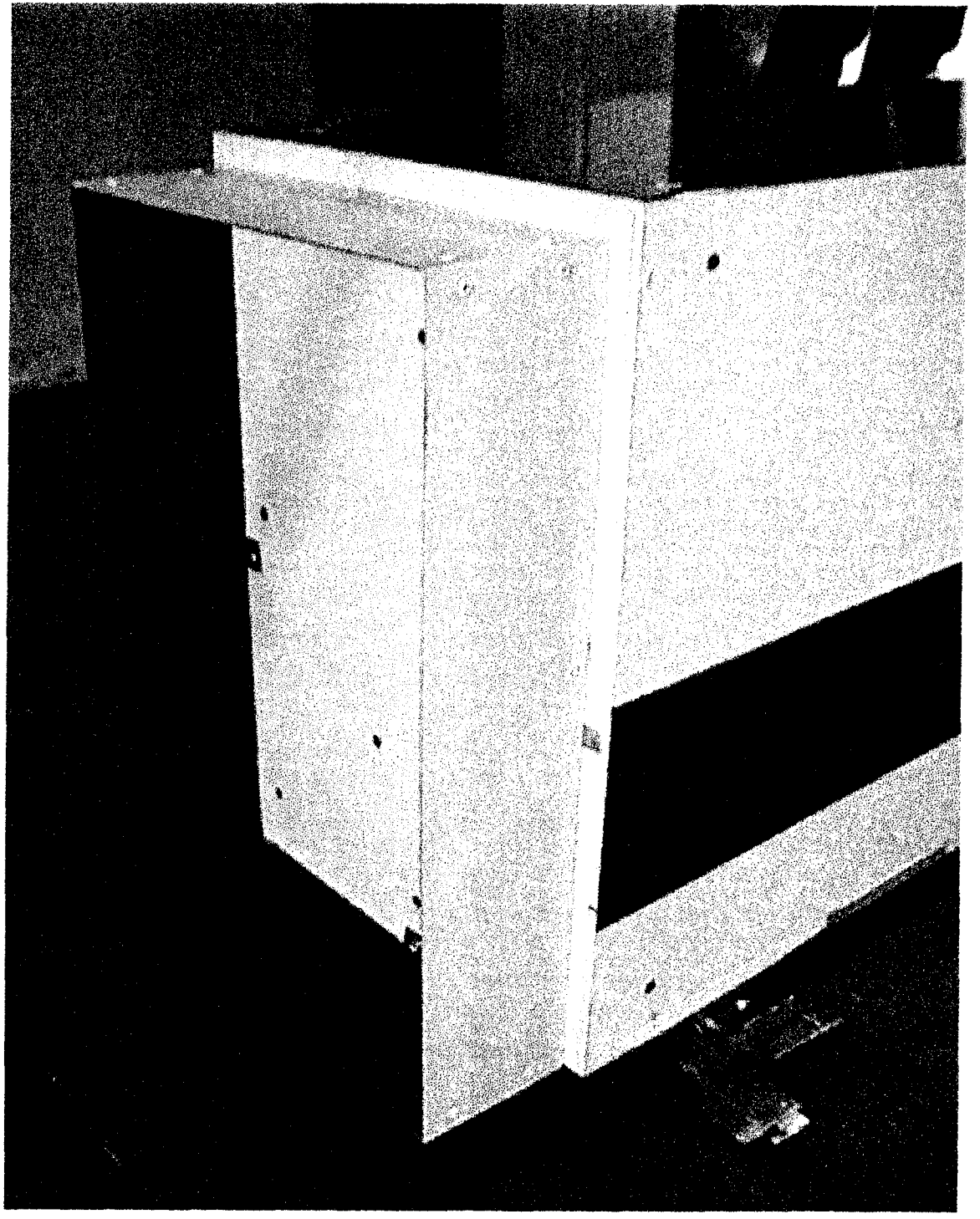
- Drag data contaminated by fouling and sloppy lever train
  - One of the side-force scales has loose bearing
  - Drag data for negative yaw is poor
  - Positive yaw data is good
- PSP data noisy but usable - at very low end of measurable pressure variations
- All other data looks good


Model
Installation

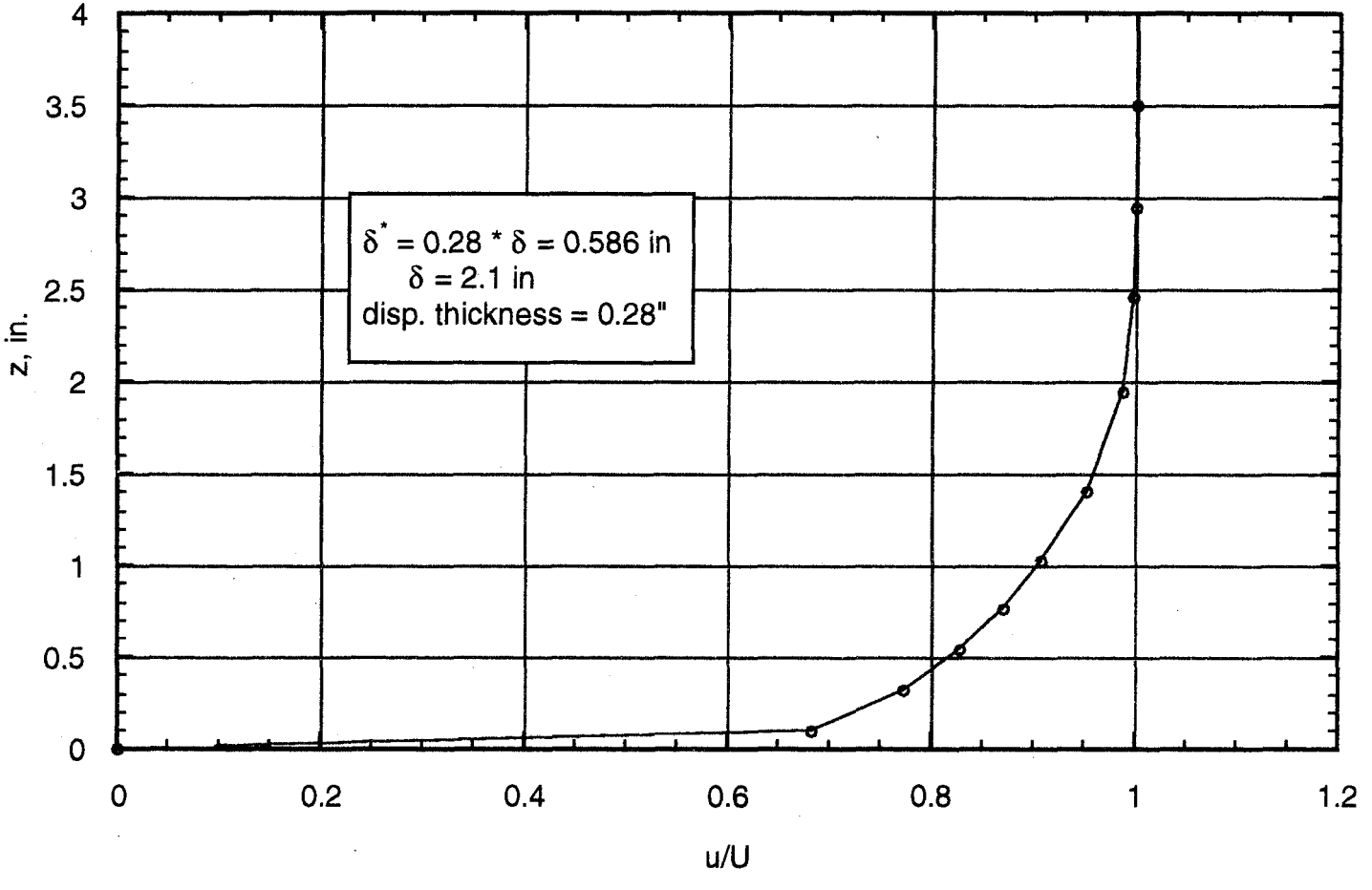

GTS Model in 7x10


Hot Film Sensors
on Model

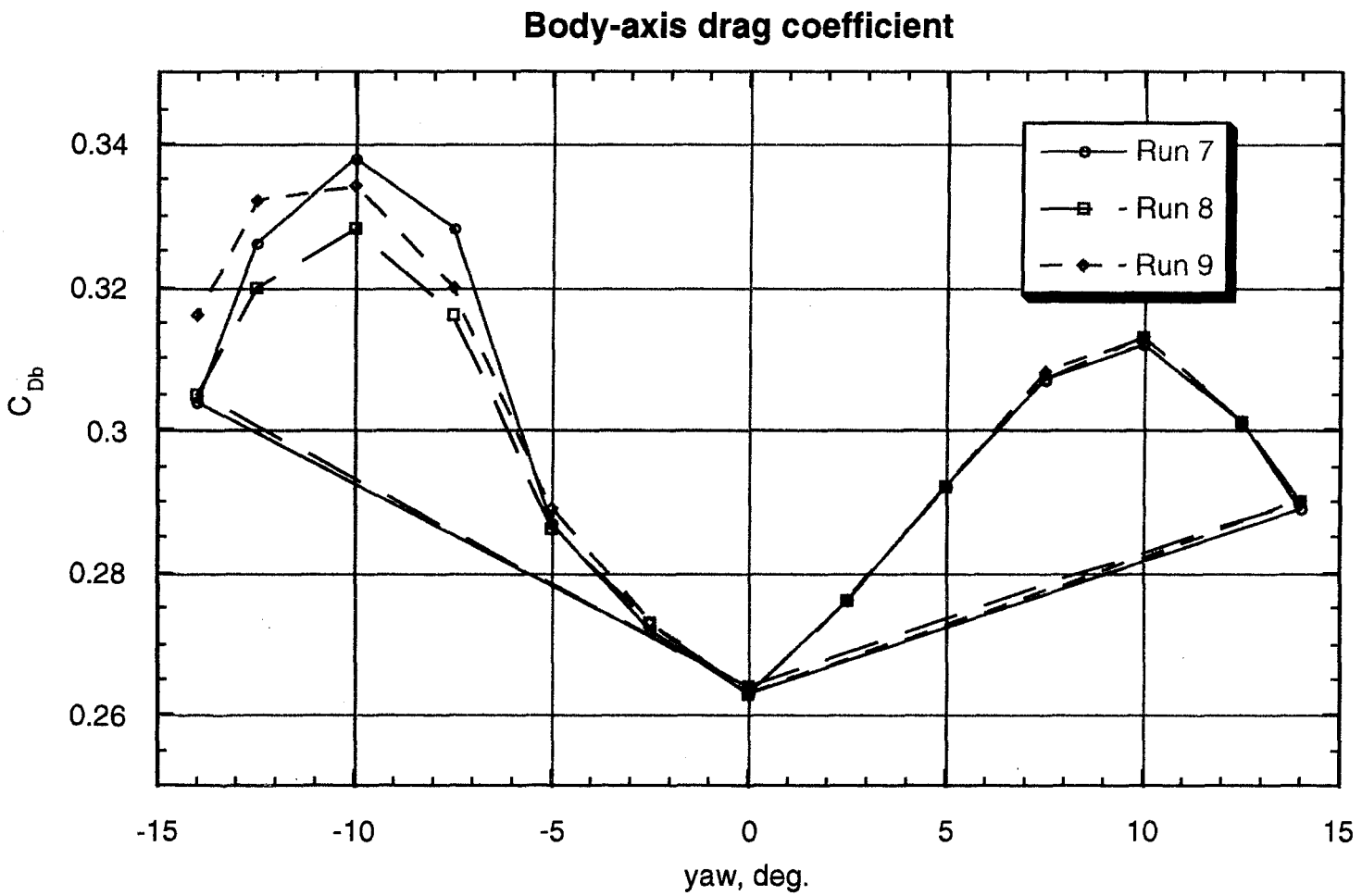
Continuum Dynamics Boattail Plates Installed on Model



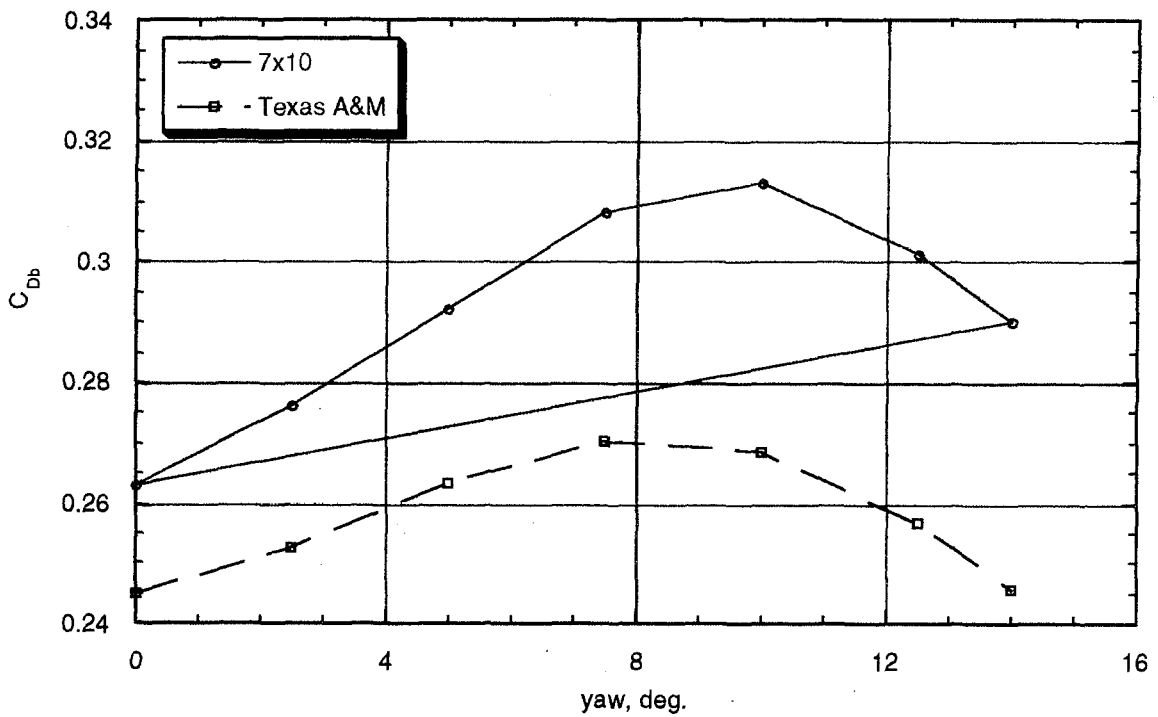
Floor Boundary Layer Profile in 7x10



Drag Repeatability

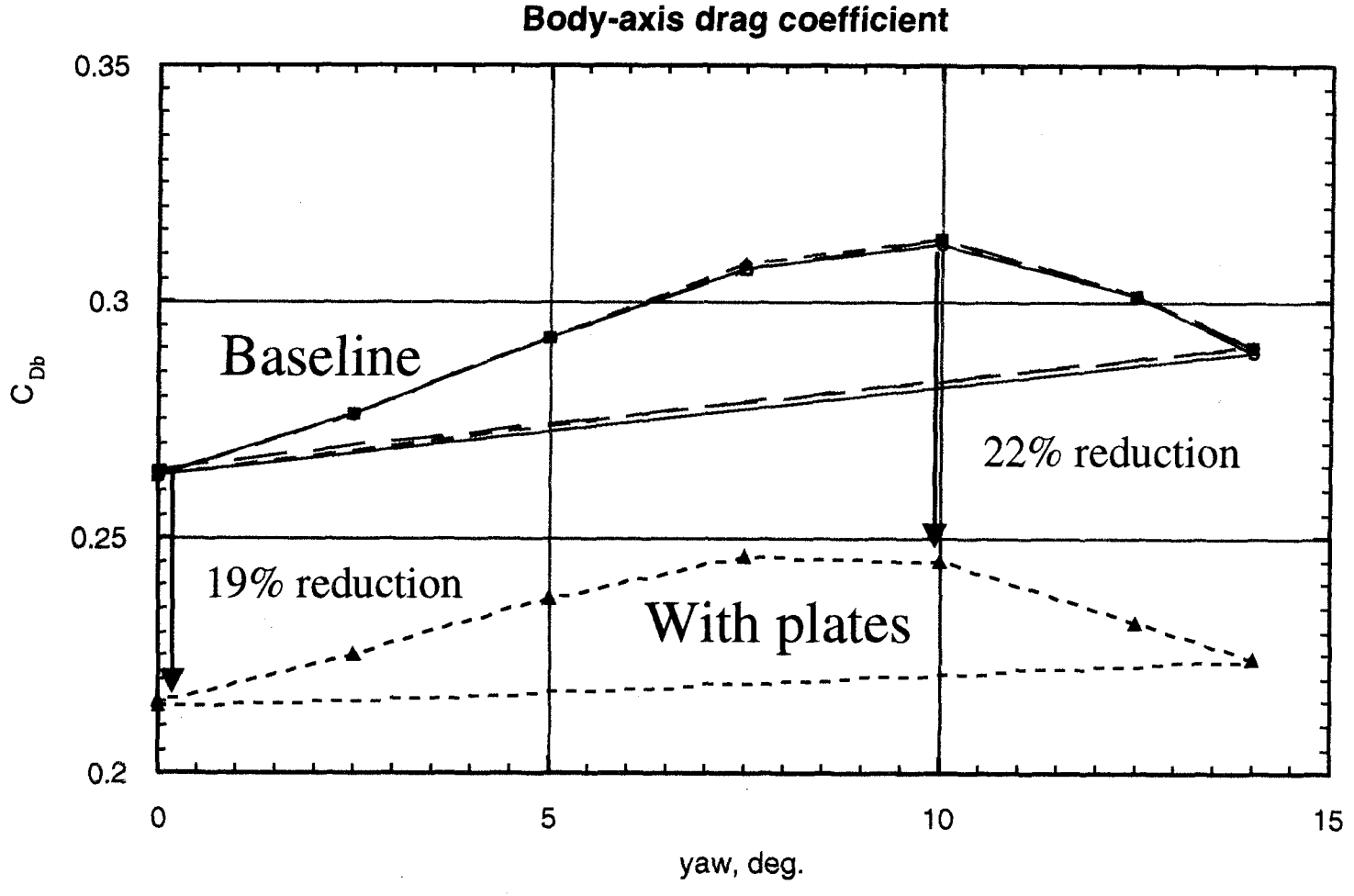


Comparison of 7x10 and Texas A&M Drag Results

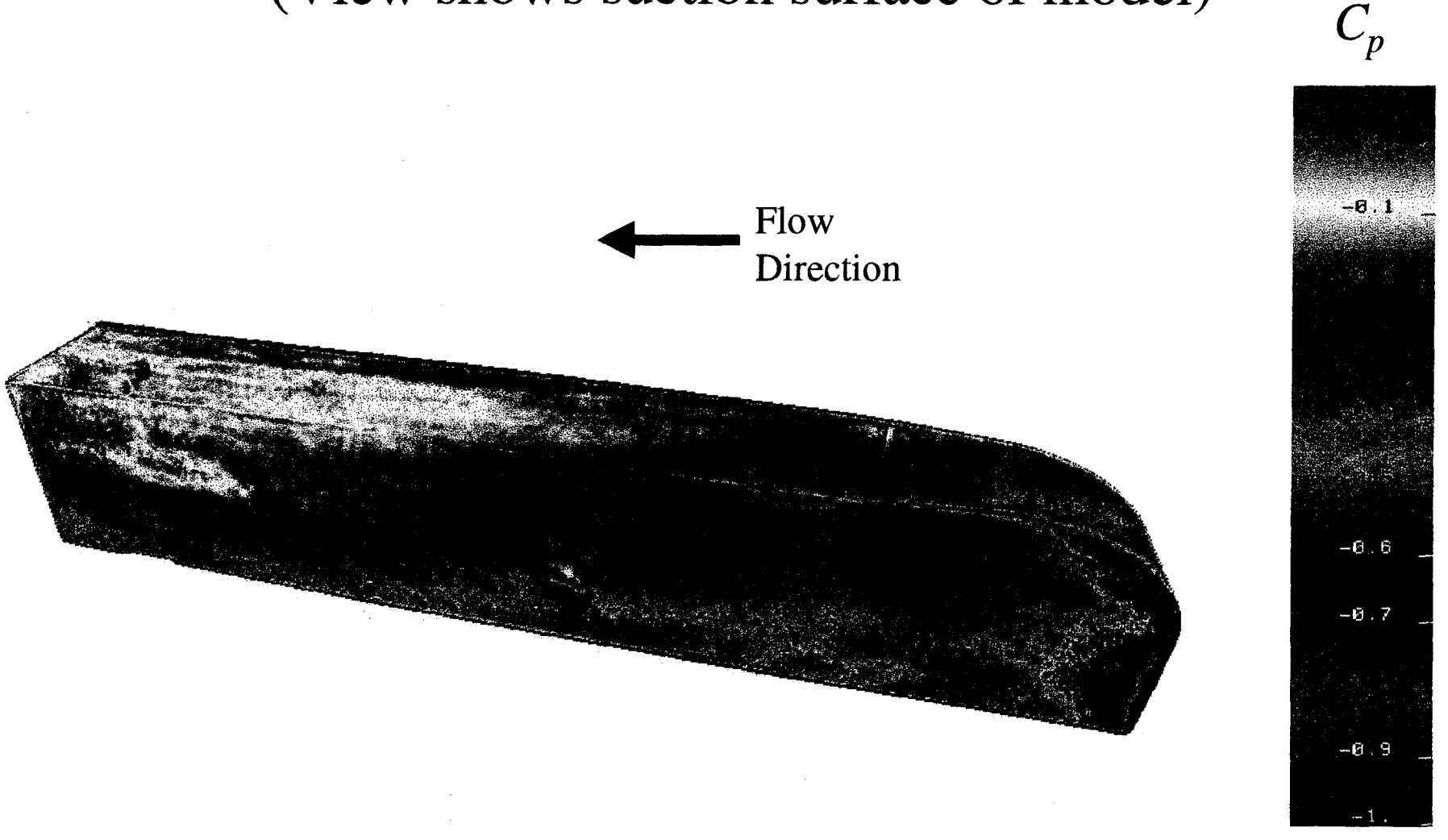


- Differences
  - Corrections applied at A&M?
  - Location of static reference pressure ring

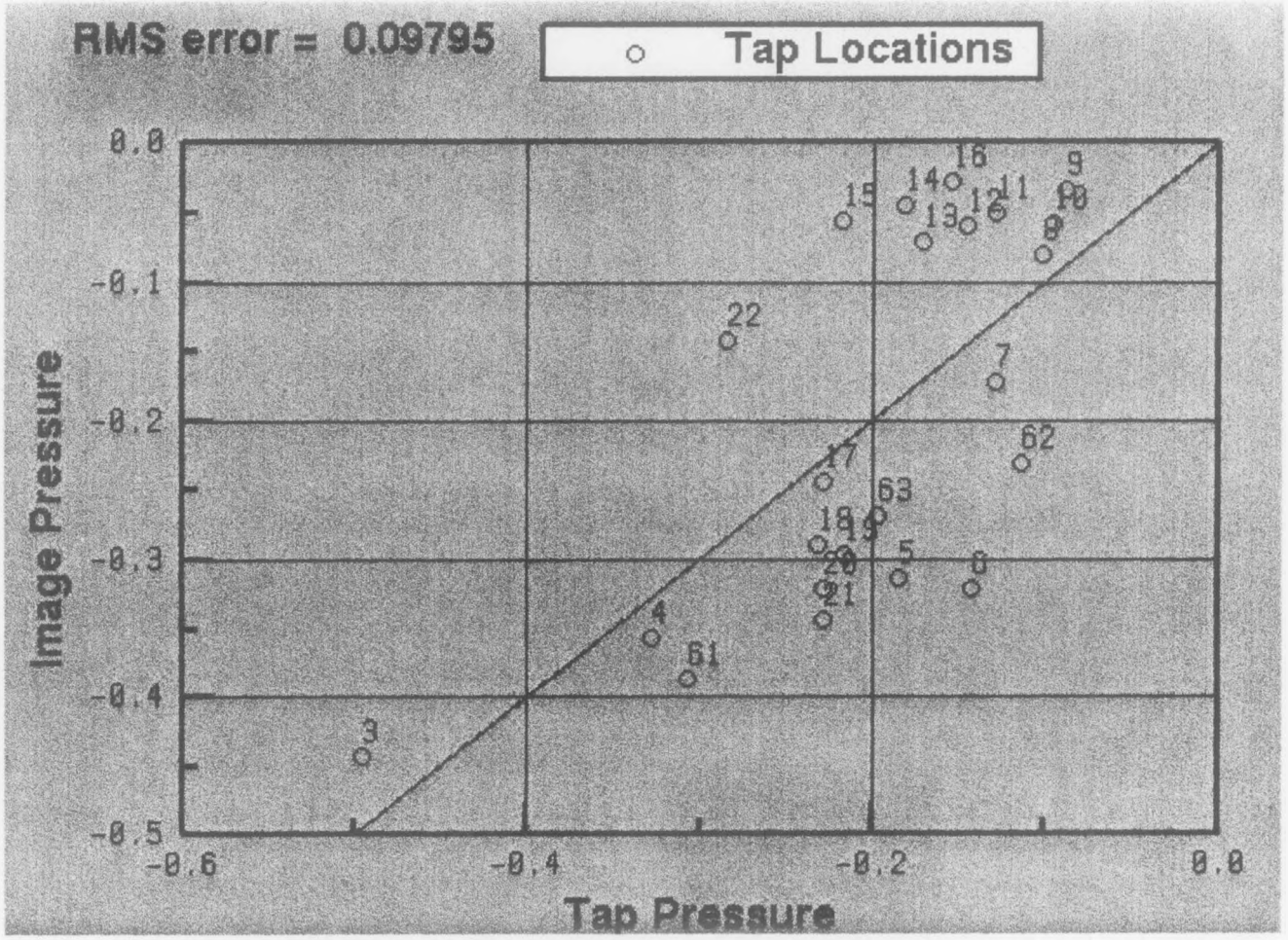
Effect of Boattail Plates on Drag



PSP Results on GTS Model in Ames 7x10
Q=88 psf, Yaw = 10°
(View shows suction surface of model)



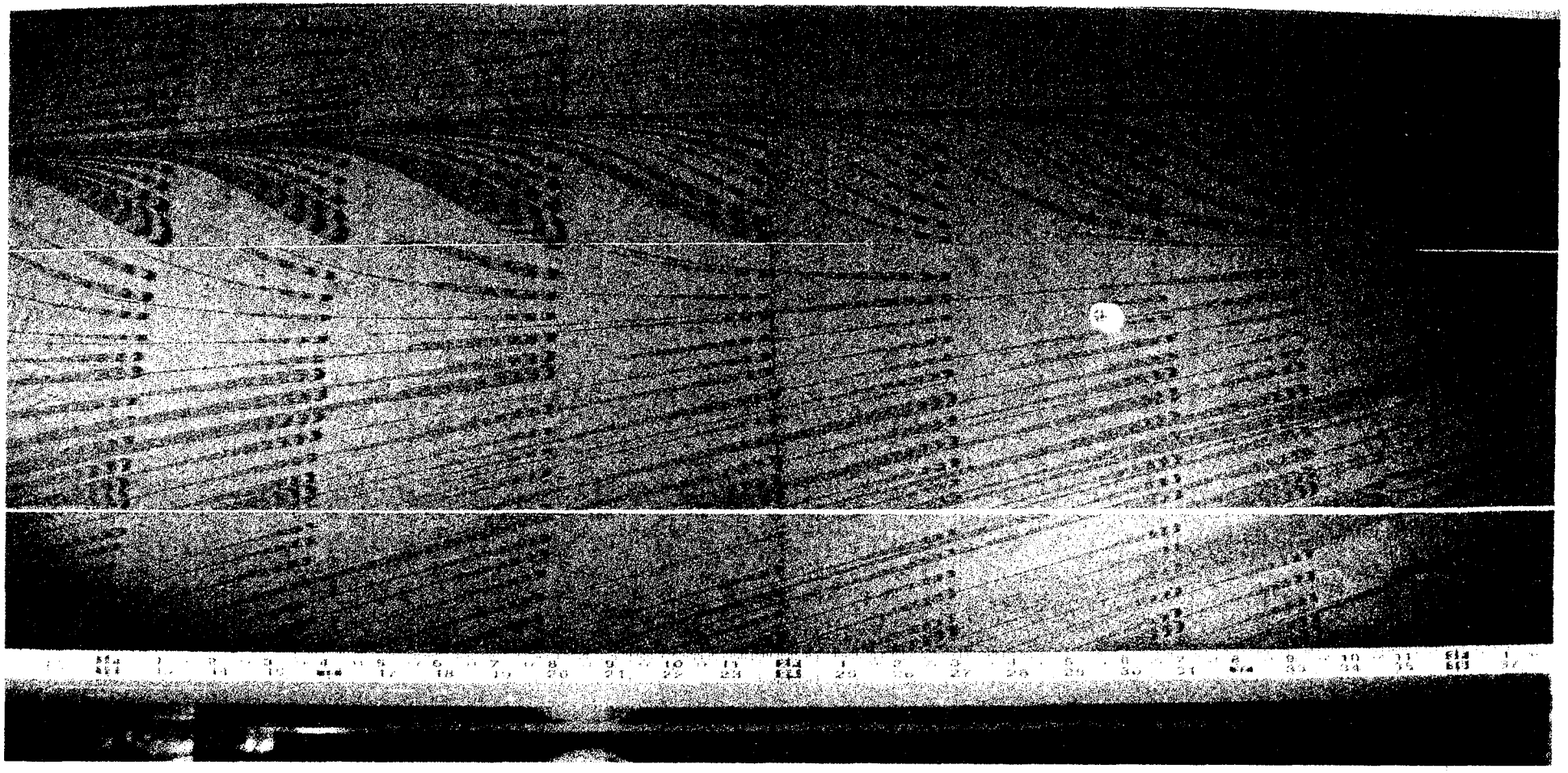
PSP Results on GTS Model in Ames 7x10
Scatter plot shows tap vs PSP comparison
For Q=88 psf, Yaw=10° case



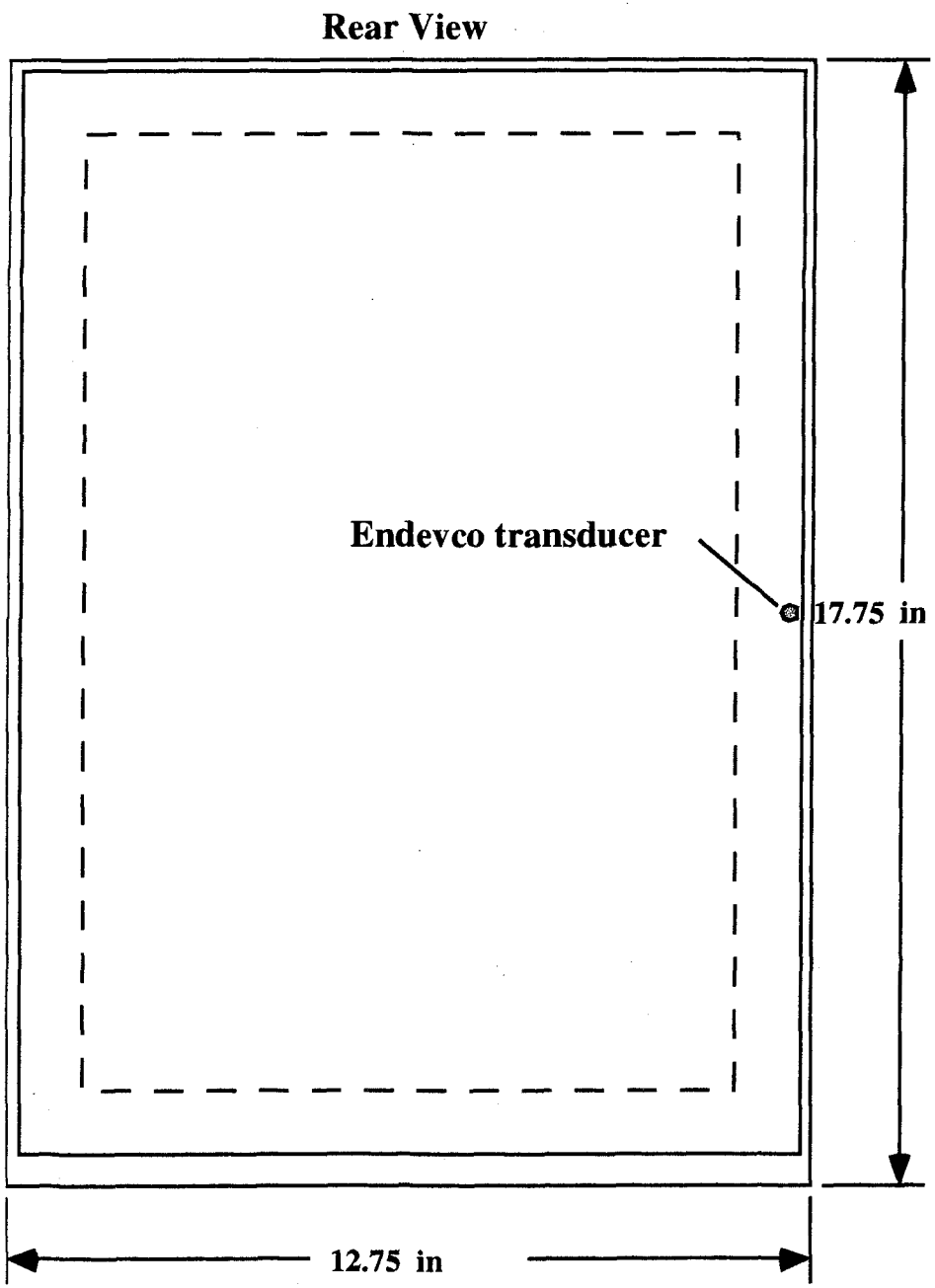
Oil film image

Top view of trailer at 10° yaw

V



Skin friction proportional to fringe spacing
(high under vortex)

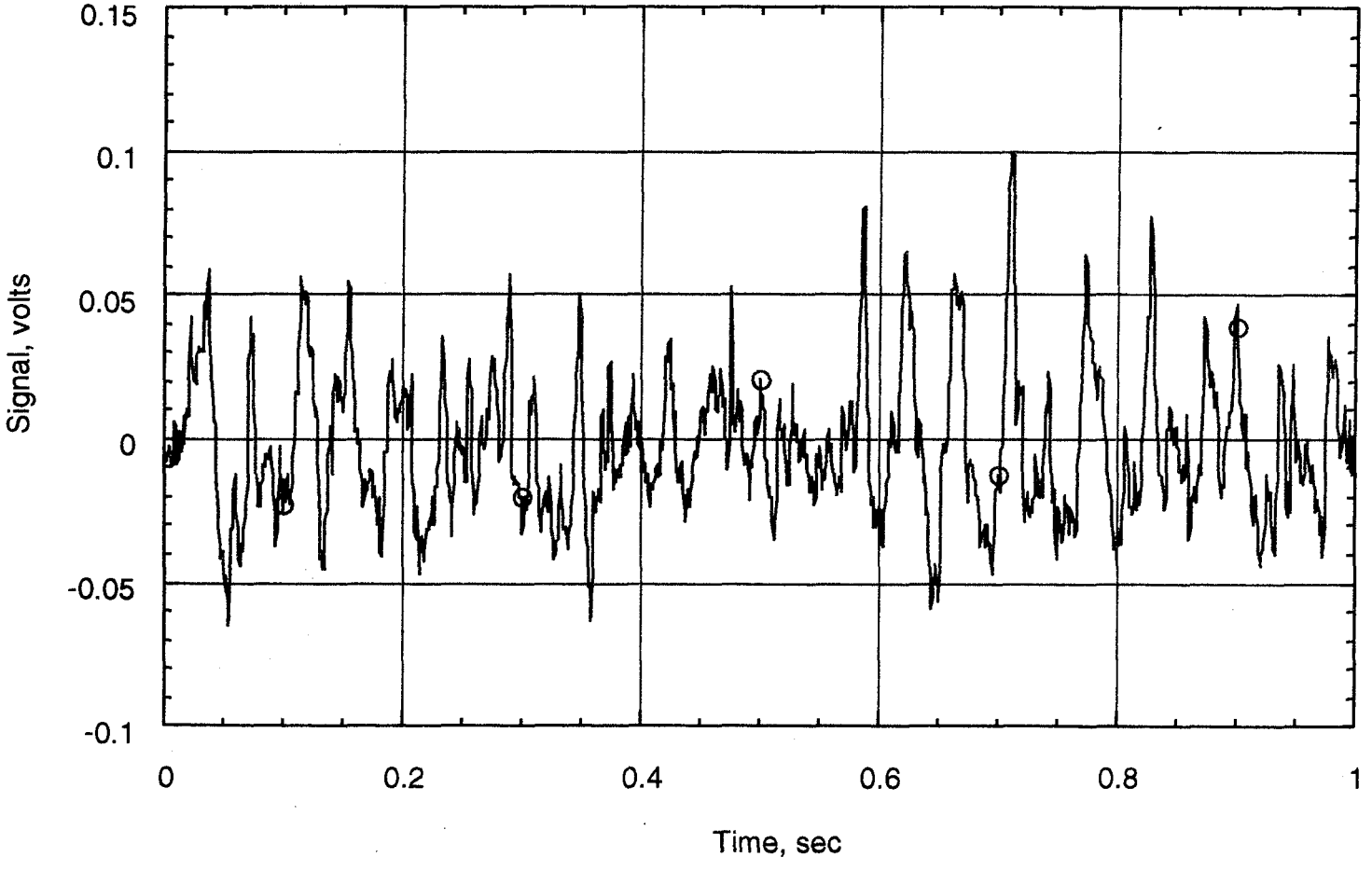


Unsteady Pressure Measurements

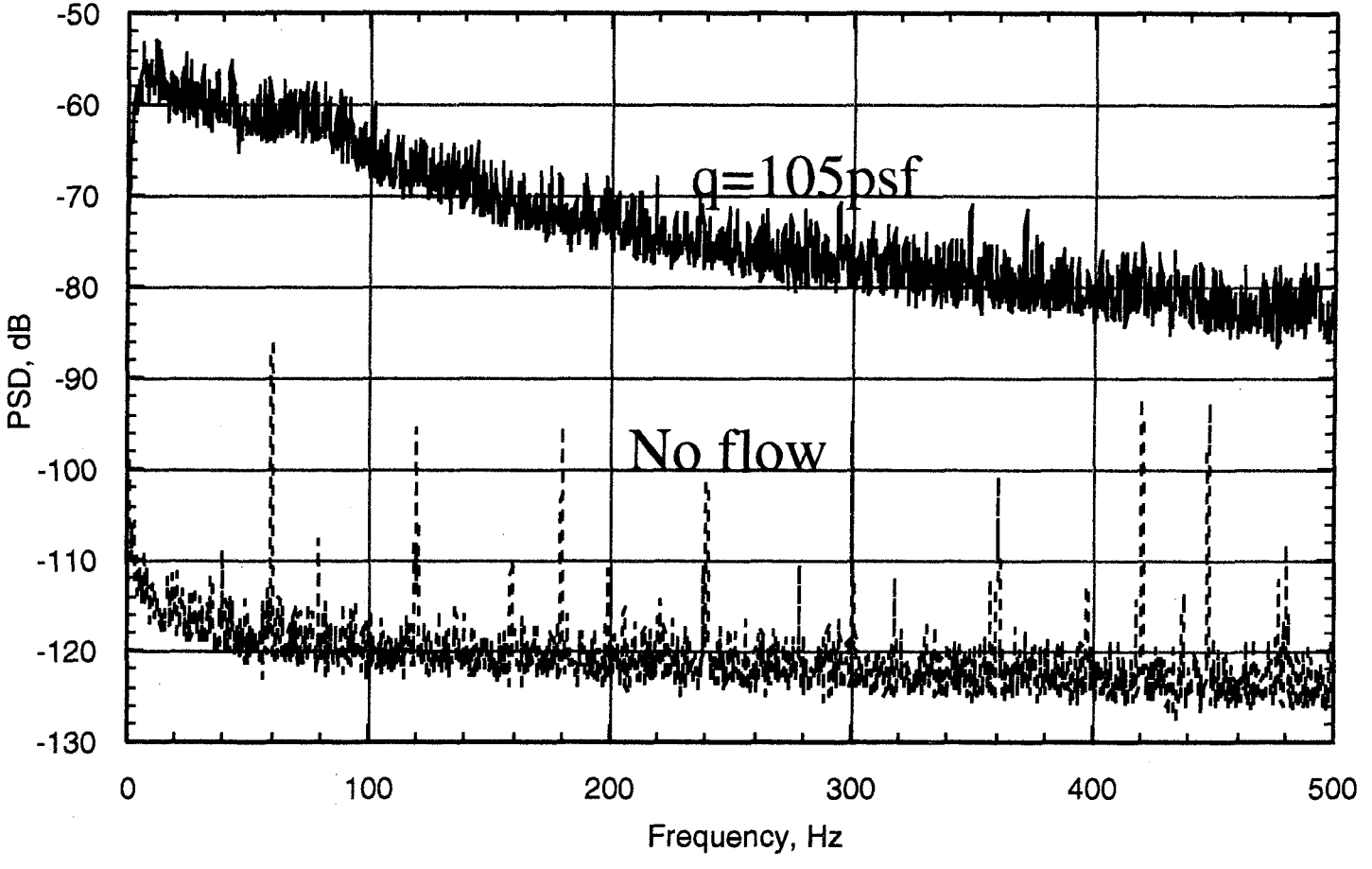
- 15 psia transducer
- Mid-height on right side of rear door (nose right is positive yaw)
- Center of transducer is 0.25” from side edge

Unsteady Pressure Signal

q = 105 psf, 0° yaw, baseline

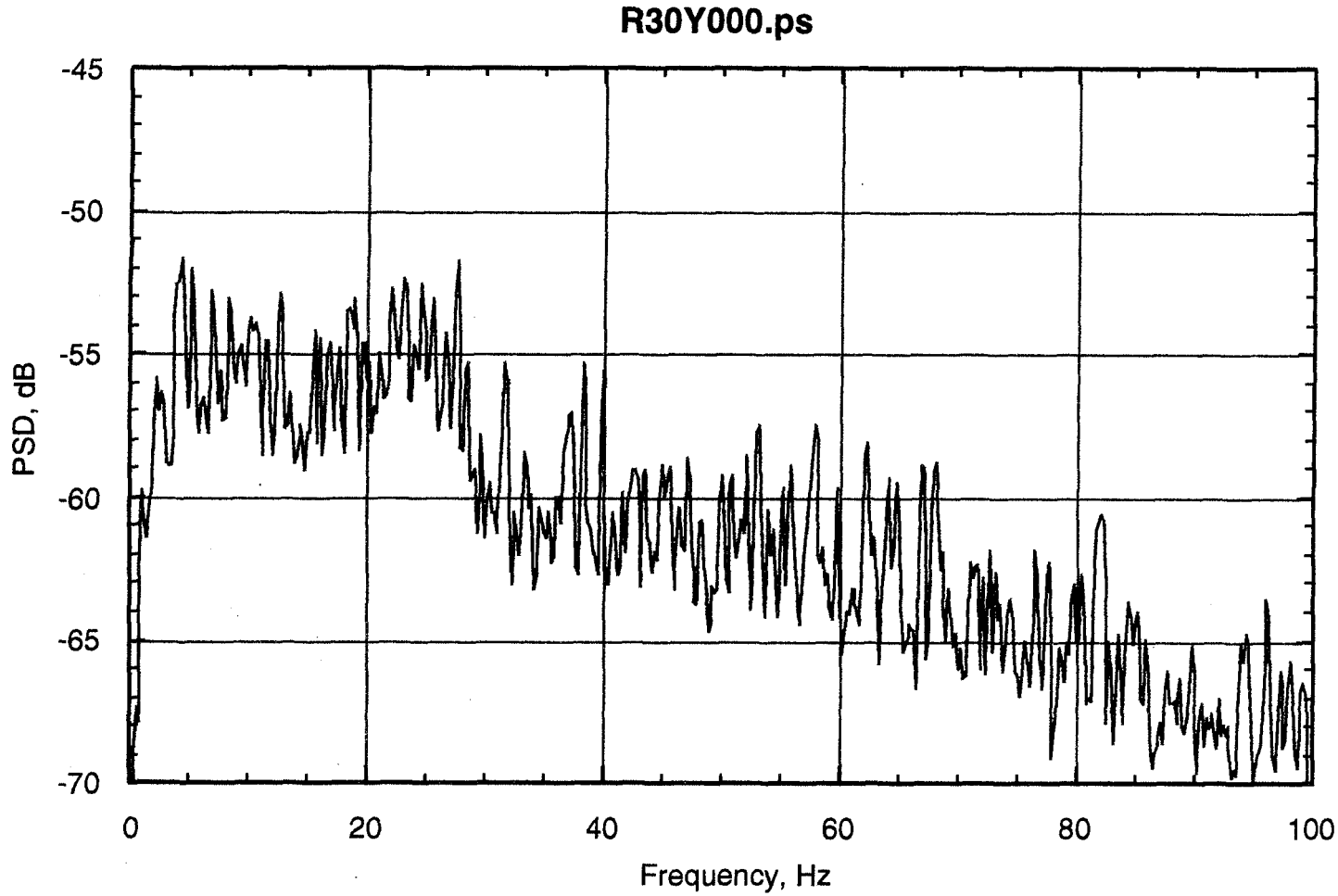


Signal Quality for Unsteady Pressures



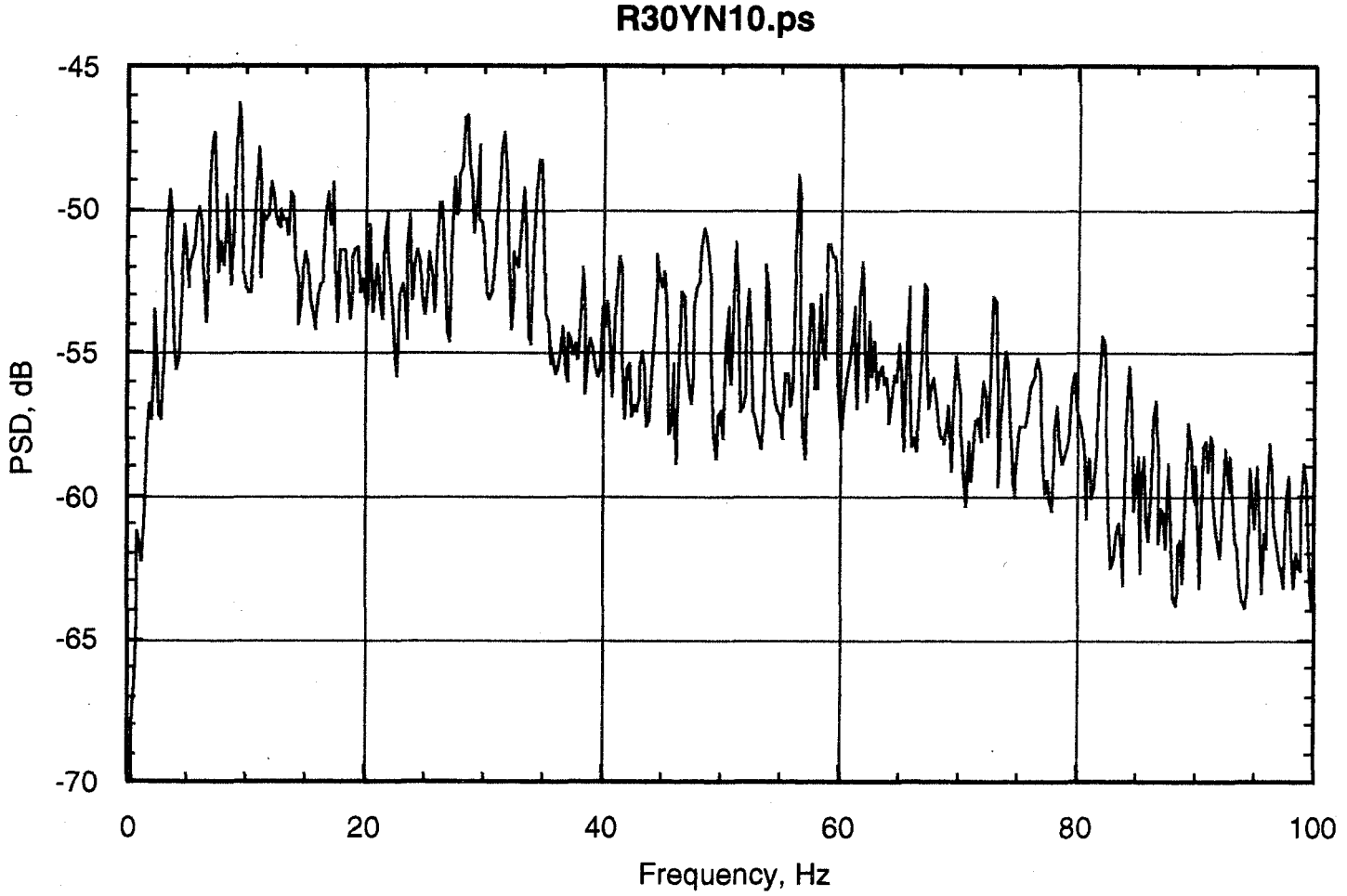
Power Spectrum of Pressure Signal

q = 105 psf , Re = 1.2M, 0° yaw, baseline



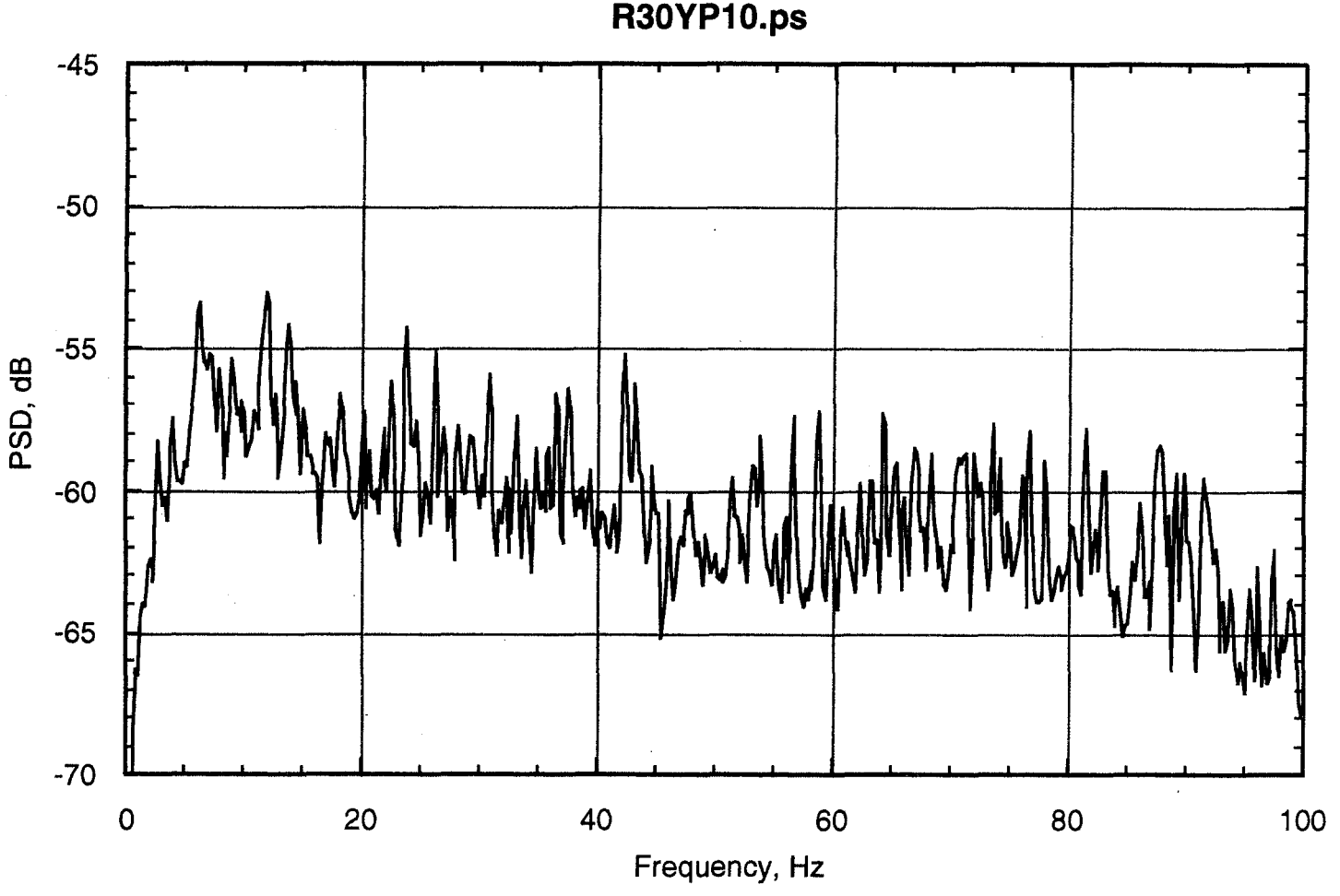
Power Spectrum of Pressure Signal

q = 105 psf , Re = 1.2M, -10° yaw, baseline



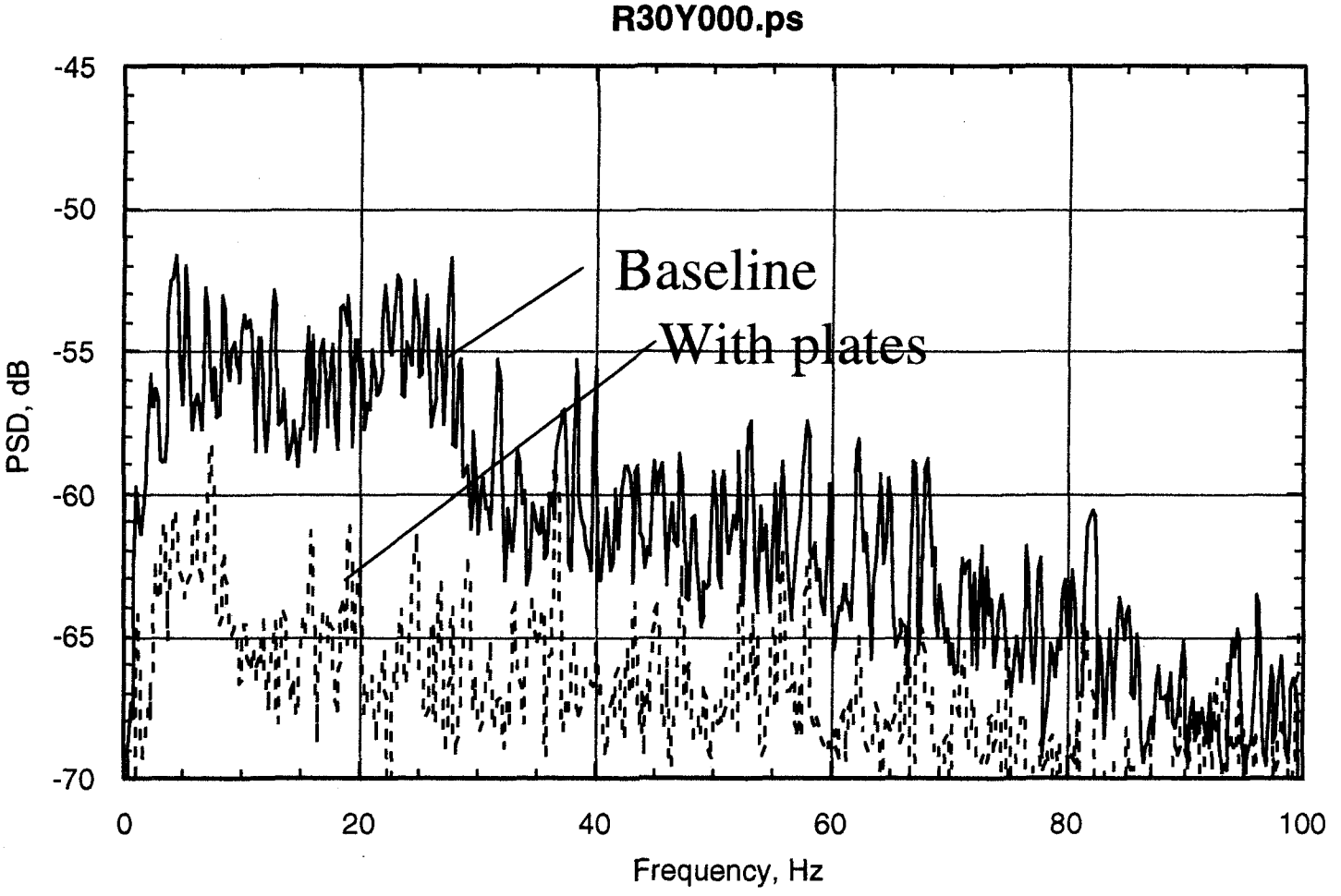
Power Spectrum of Pressure Signal

q = 105 psf , Re = 1.2M, 10° yaw, baseline



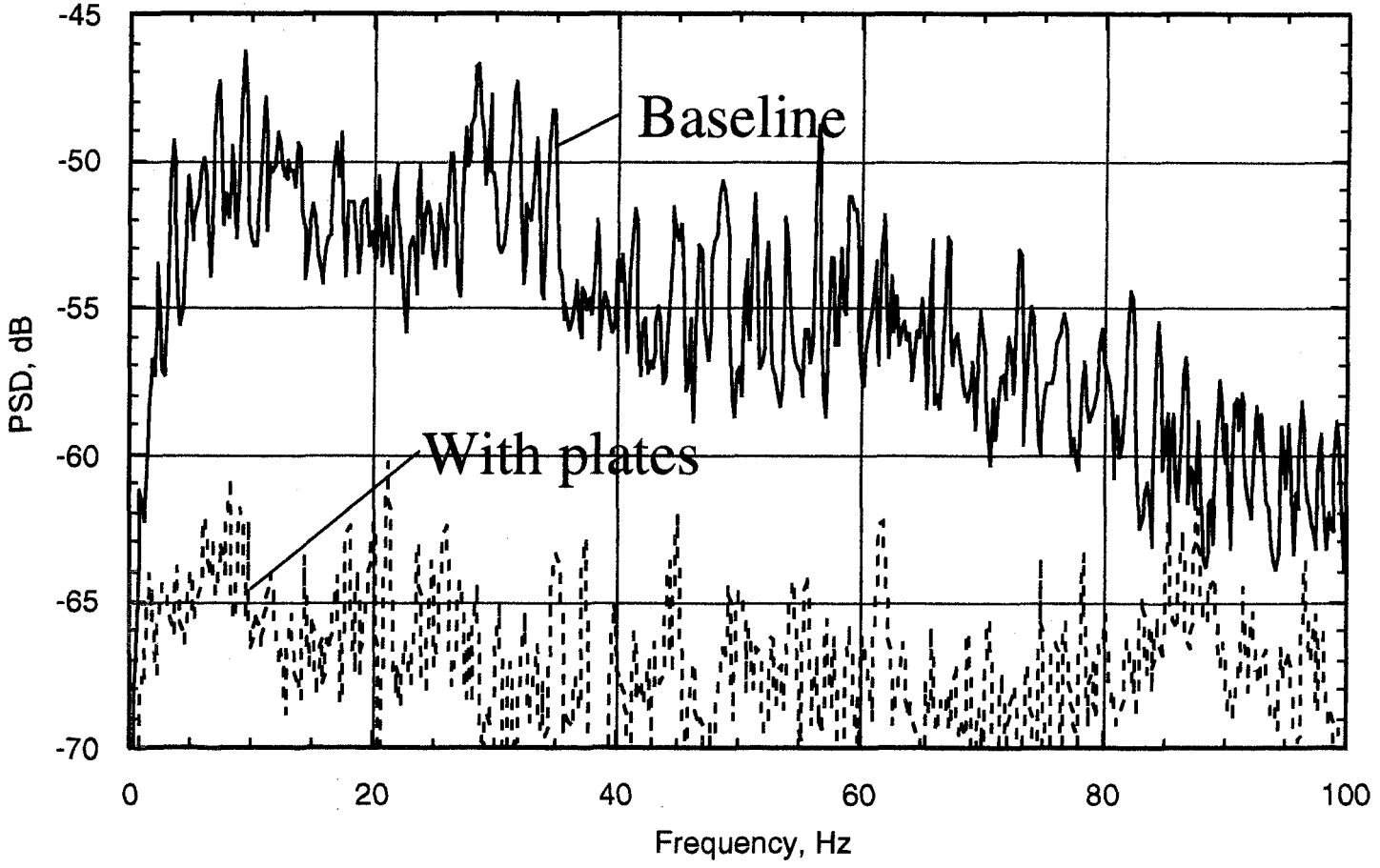
Effect of Boattail Plates on Pressure Spectrum

q = 105 psf , Re = 1.2M, 0° yaw



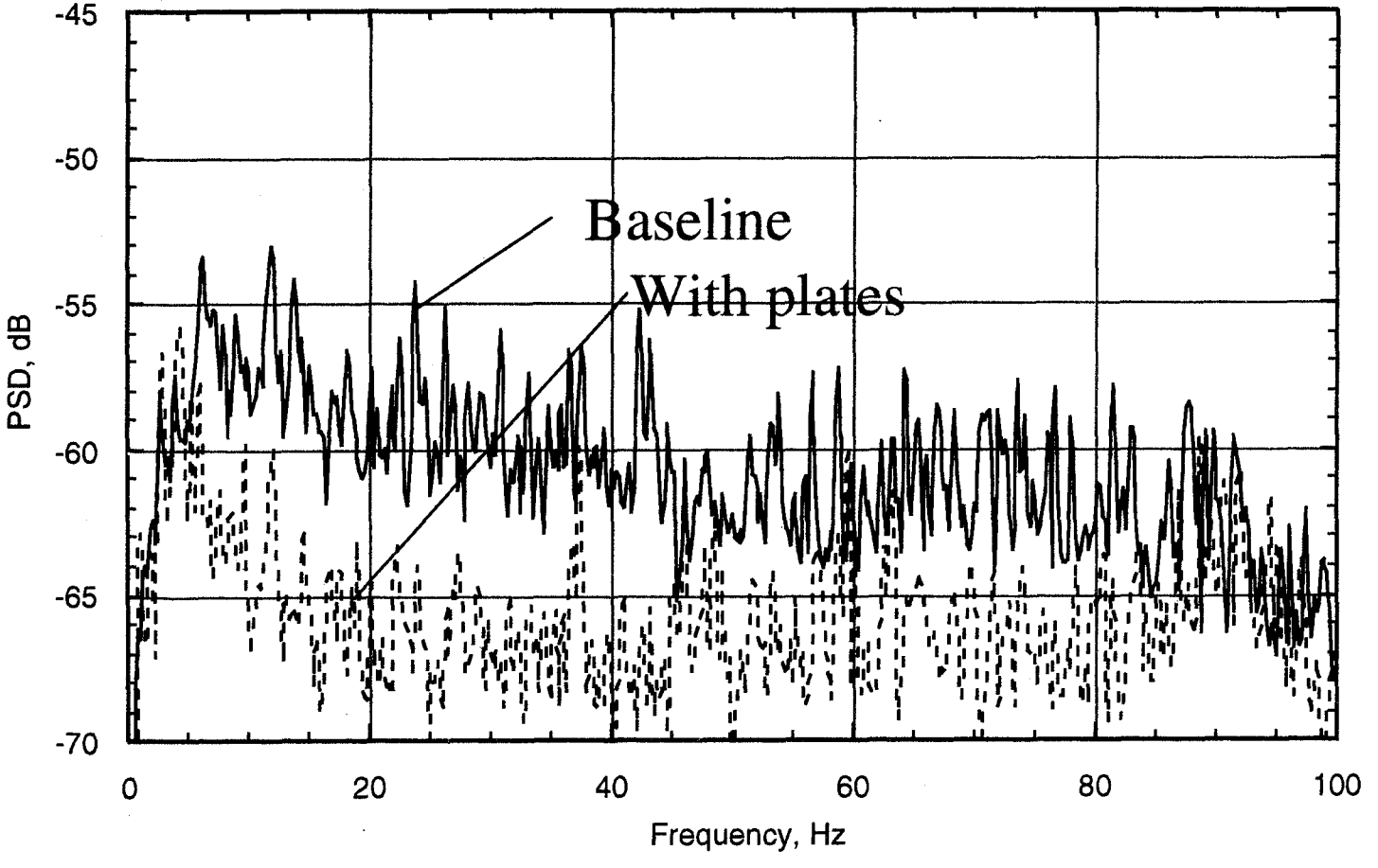
Effect of Boattail Plates on Pressure Spectrum

q = 105 psf , Re = 1.2M, -10° yaw

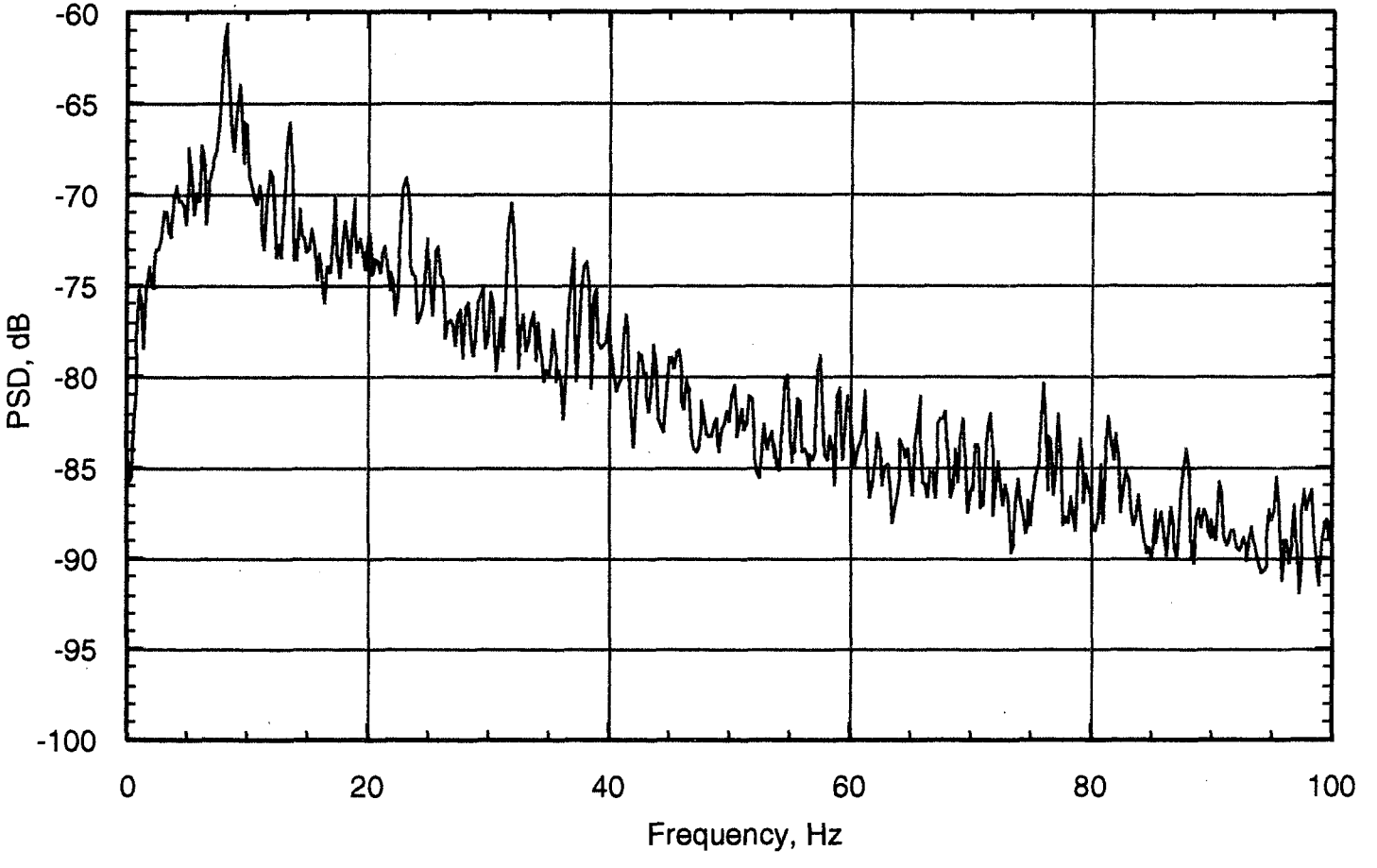


Effect of Boattail Plates on Pressure Spectrum

q = 105 psf, Re = 1.2M, 10° yaw



Pressure PSD at Low Speed
q = 15 psf, Re = 450,000, 0° yaw



Movie of Wake

Remaining Work

- Complete test
- Assemble data report
- Distribute data for validation work
  - Data format is an open issue

Plans for 12' PWT Test

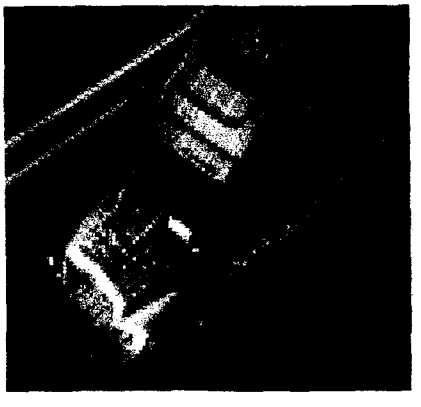
- Examine Re effects up to full-scale on 1/8th-scale model
- Determine minimum Re for various aspects of geometry
  - Gap
  - Cooling flow
  - Mirror
  - Base-drag reduction
  - ?
- CFD validation data at range of Re

Aerodynamics of Heavy Vehicles

Fred Browand
Mustapha Hammache
Staff

Glen Landreth
David Sandler
Patricia Wall
Students

Aerospace and Mechanical Engineering
University of Southern California



LLNL
March 11, 1999

Introduction

- Brief discussion of several relevant publications
- Progress in the laboratory
- Computation
- Recent DPIV measurements

- **"Detached-eddy simulation of an airfoil at high angle of attack", M. Shur, P.R. Spalart, M. Strelets, A. Travin,** *Proceedings of the 1st AFOSR Conference on DNS/LES, Ruston, LA, August 1997*
- **"Comments on the feasibility of LES for wings, and on a hybrid RANS/LES approach", P.R. Spalart, W-H. Jou, M. Strelets, S.R. Allmaras**

  - 200,000 grid points, fully 3-D calculation
  - RANS formalism for attached boundary layers
  - LES sufficiently far away from wall
  - Switches between the two automatically, (this is DES)
  - Captures bulk of unsteady flow behavior

- **"The effect of front-edge rounding and rear-edge shaping on the aerodynamic drag of bluff vehicles in ground proximity", K.R. Cooper,** *SAE Technical Paper 850288, 1985*

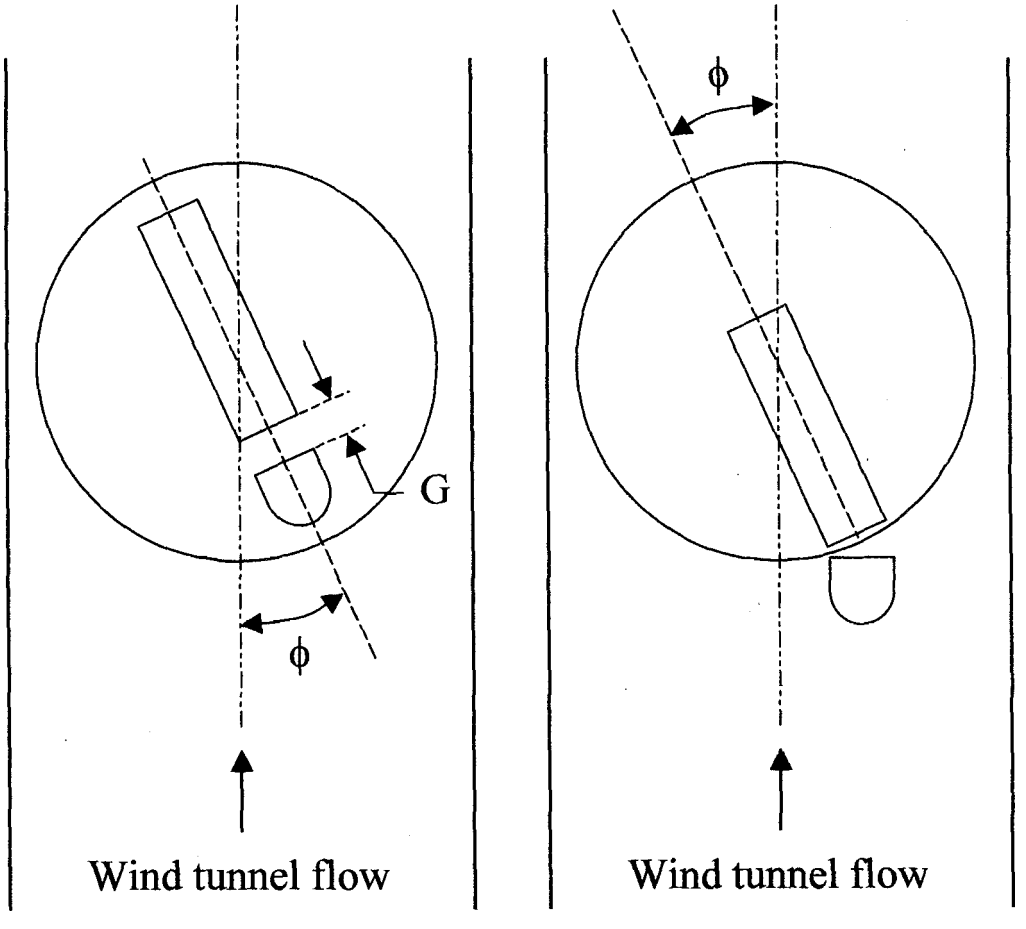
  - Preventing separation at relatively sharp front edges can have a dramatic effect on the drag of a bluff body

- **"Flight-determined subsonic lift and drag characteristics of seven lifting-body and wing-body reentry vehicle configurations with truncated bases", E.J. Saltzman, K.C. Wang, K.W. Iliff,** *AIAA 99-0383, 1999*
- **"A reassessment of heavy-duty truck aerodynamic design features & priorities", E.J. Saltzman, R.R. Meyer, Jr.,** *Preliminary Report, NASA Dryden Flight Research Center, 1998*

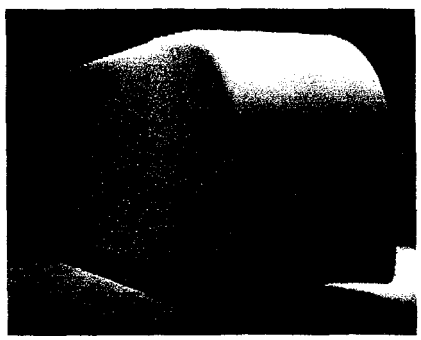
  - A relationship exists between fore-body drag and base pressure coefficient for many bluff-base aerodynamic shapes. This may include heavy trucks.
  - If the form of the relationship is postulated, the minimum drag configuration can be determined

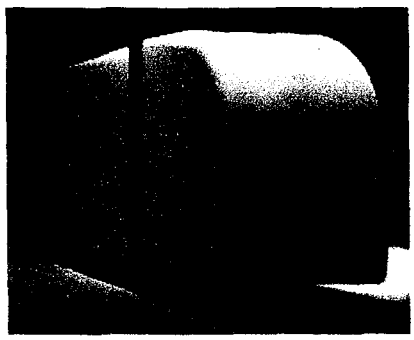
Progress in the laboratory

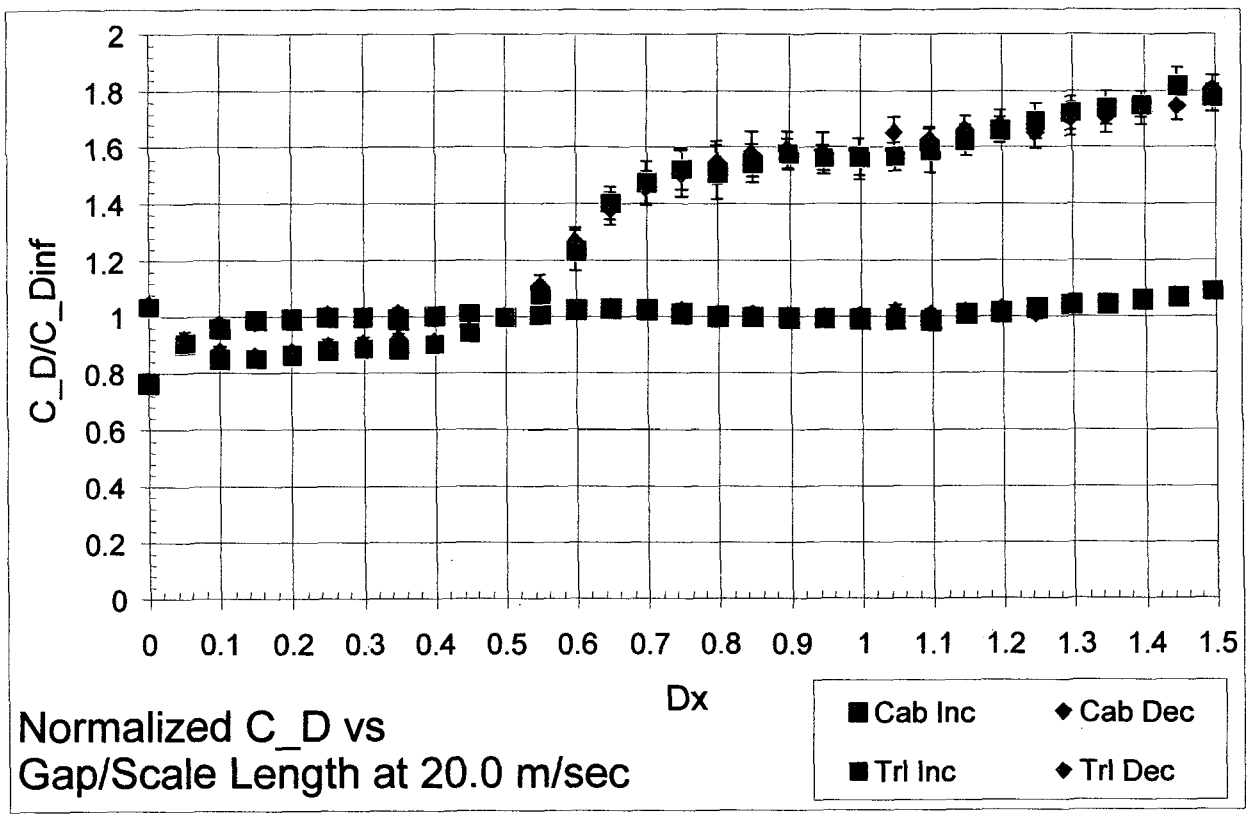
- Work area being remodeled (University pays $25,000)
- Yaw turntable will be operational in April

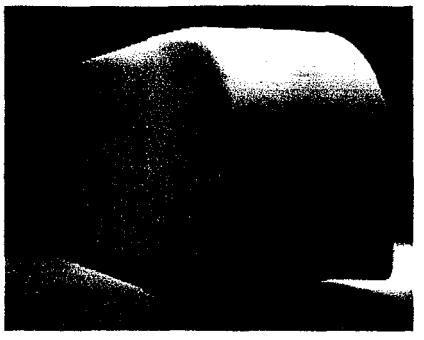


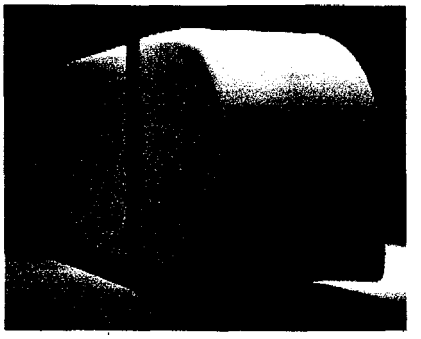
- SNL Truck Model has been fabricated and operated in the wind tunnel

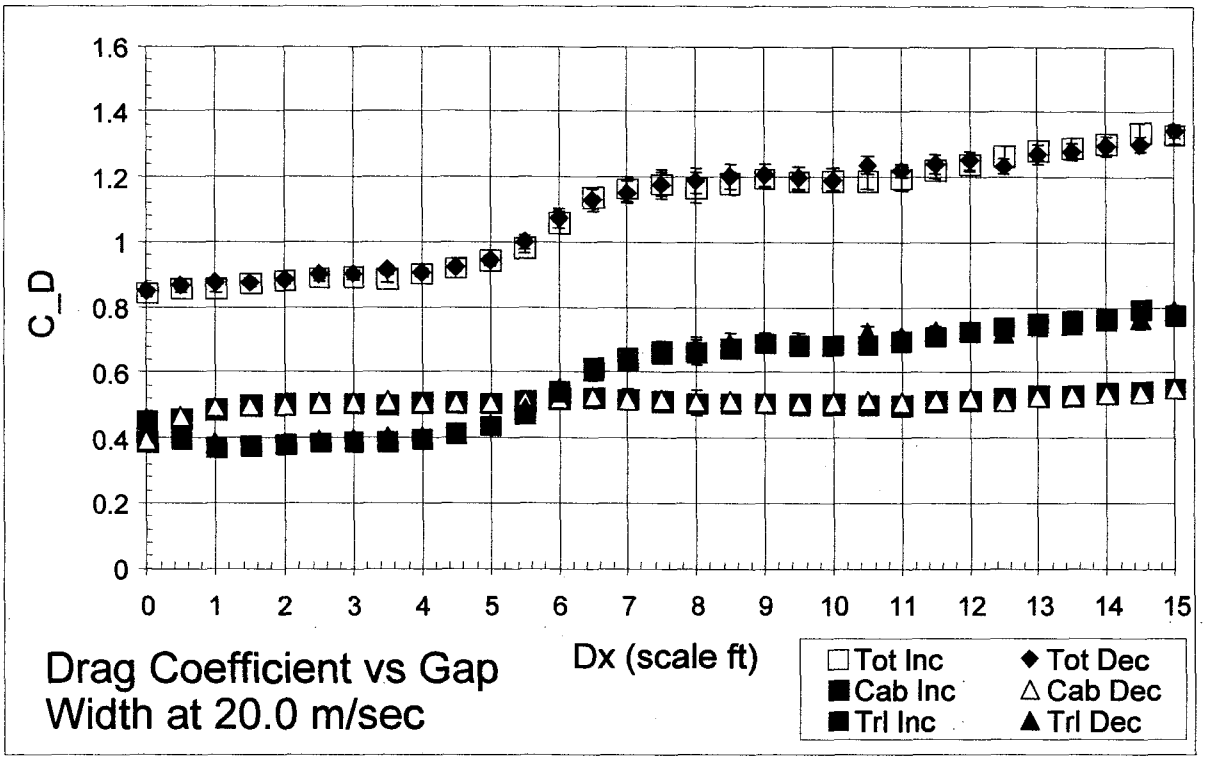




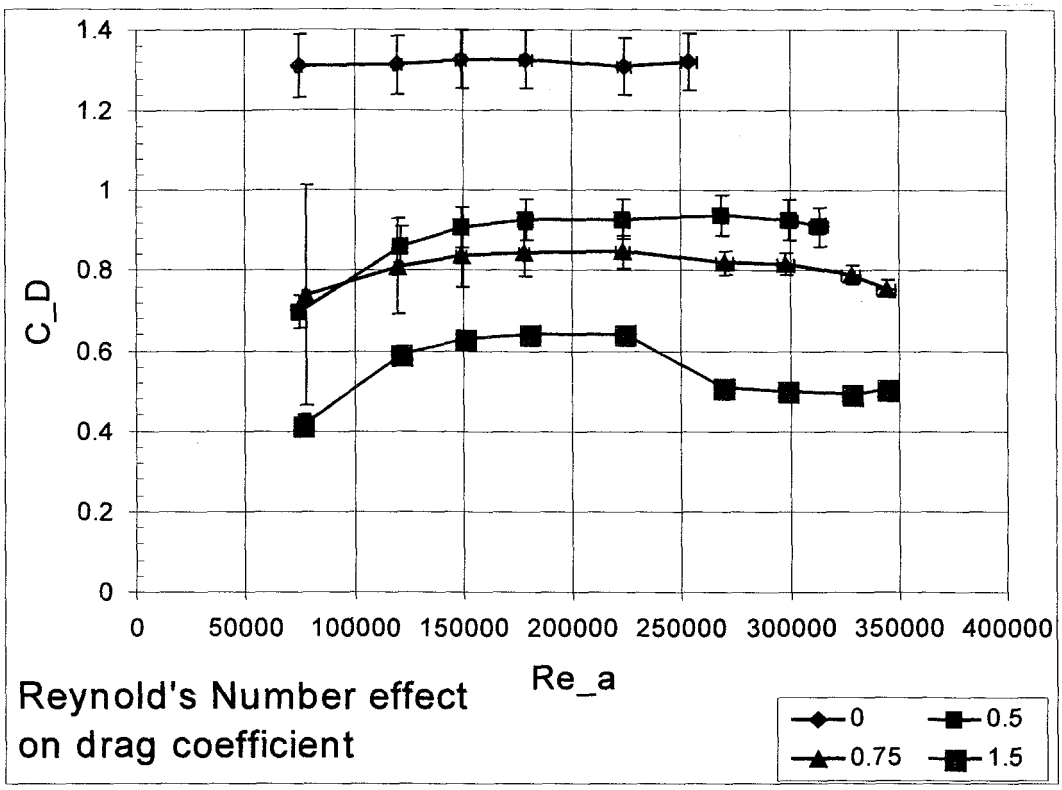


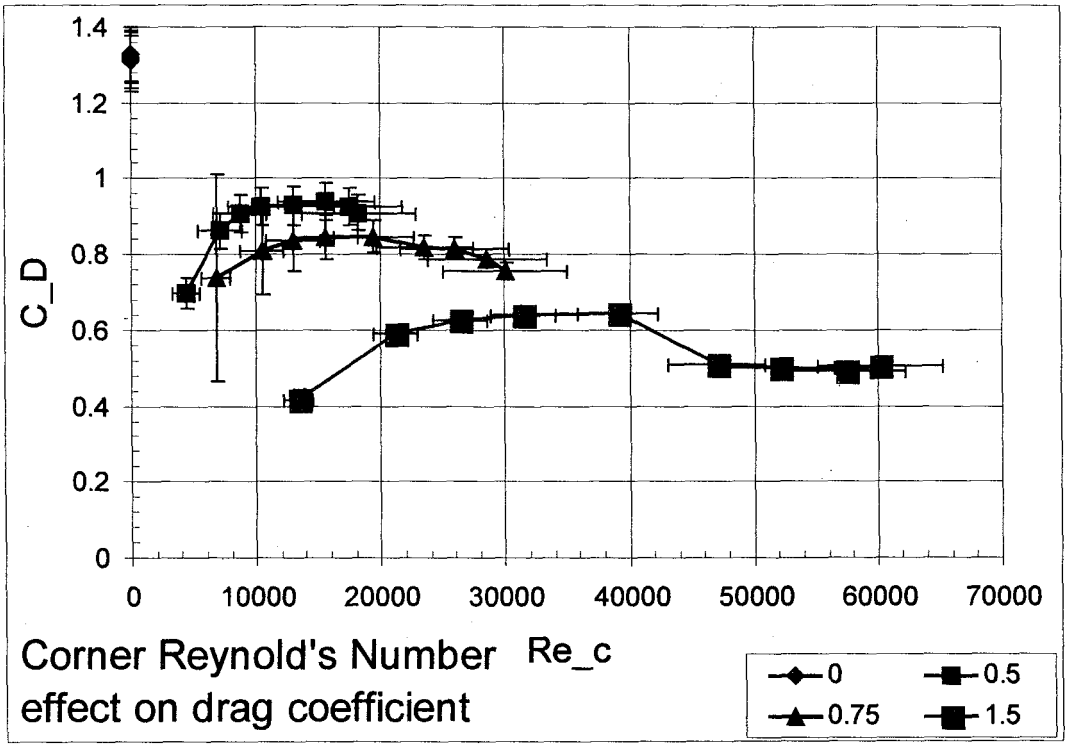






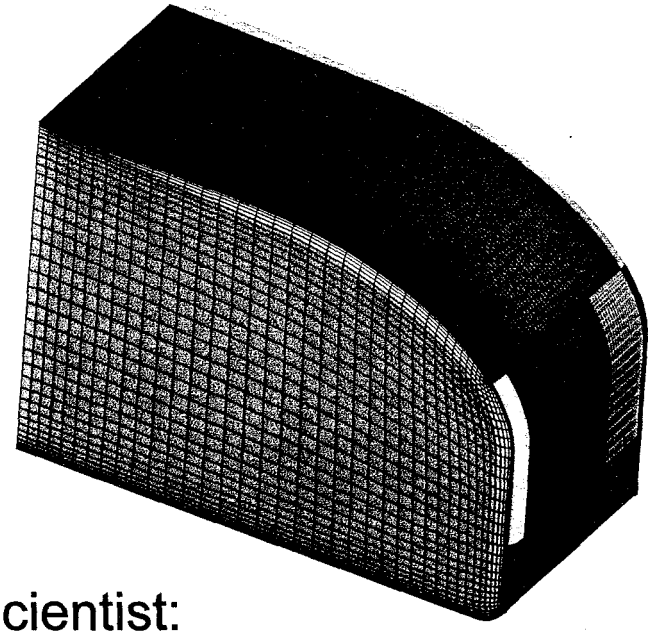
Drag Coefficient vs Gap Width at 20.0 m/sec


1.4
1.2
1
0.8
0.6
0.4
0.2
0
C_D
0
50000
100000
150000
200000
250000
300000
350000
400000
Re_a
Reynold's Number effect
on drag coefficient
0
0.5
0.75
1.5


1.4
1.2
1
0.8
0.6
0.4
0.2
0
C_D
0
10000
20000
30000
40000
50000
60000
70000
Re_c
Corner Reynold's Number
effect on drag coefficient
0
0.5
0.75
1.5

Computations

- Panel code calculations PMARC



- Visiting Scientist:

  Dr. Dieter Schwamborn
  Head, CFD Group
  Institute for Fluid Mechanics
  DLR, Gottingen (Germany)

- DES:Smooth cab-trailer (with gap)
  SNL Model (with cab-trailer gap)

Topics of Discussion

- Description of flow facilities
- Description of DPIV capabilities
  - Maximizing accuracy
  - Maximizing spatial resolution
  - Treating solid boundaries
- Experiments
  - Vehicle platooning
  - SNL truck model with gap
- The NASA-Ames PIV data at low speed

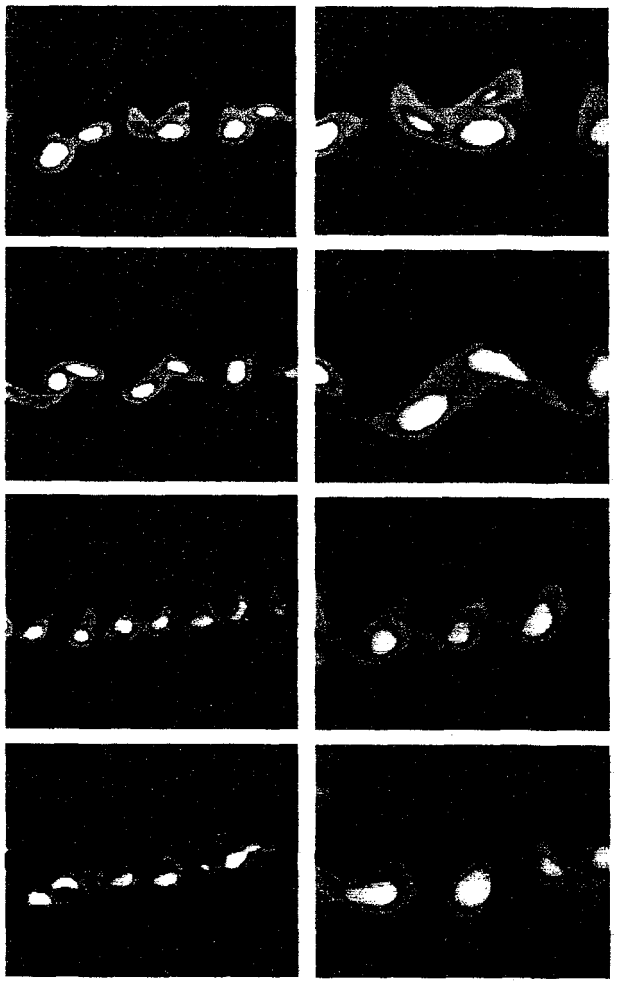
Flow facilities

- Dryden wind tunnel
  - Top speed 44 m/s (100mph)
  - Test section 1.3mx1.3m (53"x53")
- Nissan/Linac wind tunnel
  - Moving ground belt
  - Top speed 90 m/s
  - Test section 0.9mx1.1m (36"x42")

DPIV capabilities

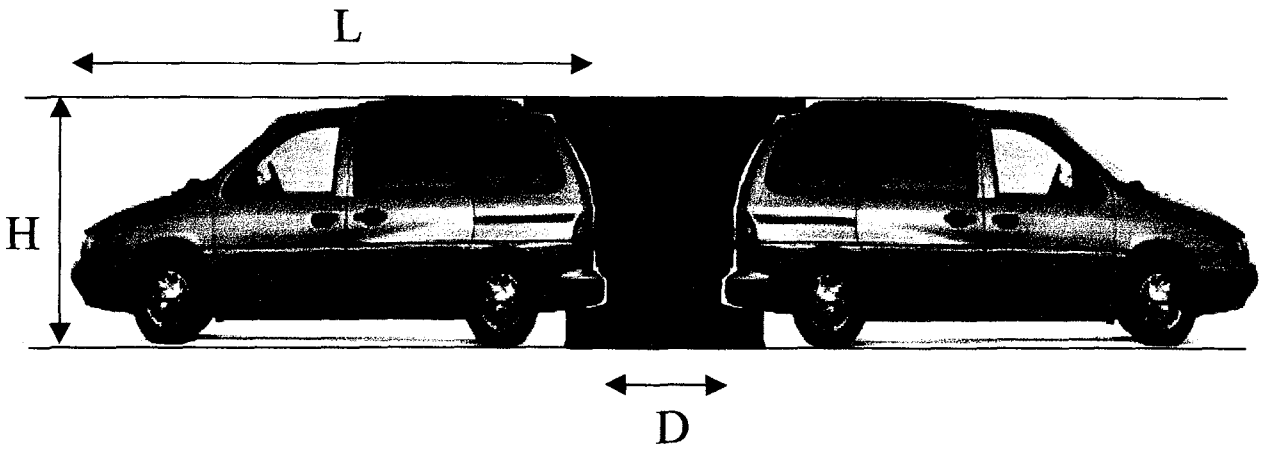
- Two-dimensional PIV based on cross-correlation technique
- Dual channel CCD camera
  - 1 million pixels
  - 15 images pairs/sec
- Dual Nd-Yag laser
  - 160 mJ/pulse
  - 10 Hz
- Option for variable resolution
  - wide flow field
  - maximum spatial resolution
- CIV software tested for reliability and speed
- No-slip condition imposed at the walls
- Special treatment of the data close to the walls

Adaptive resolution



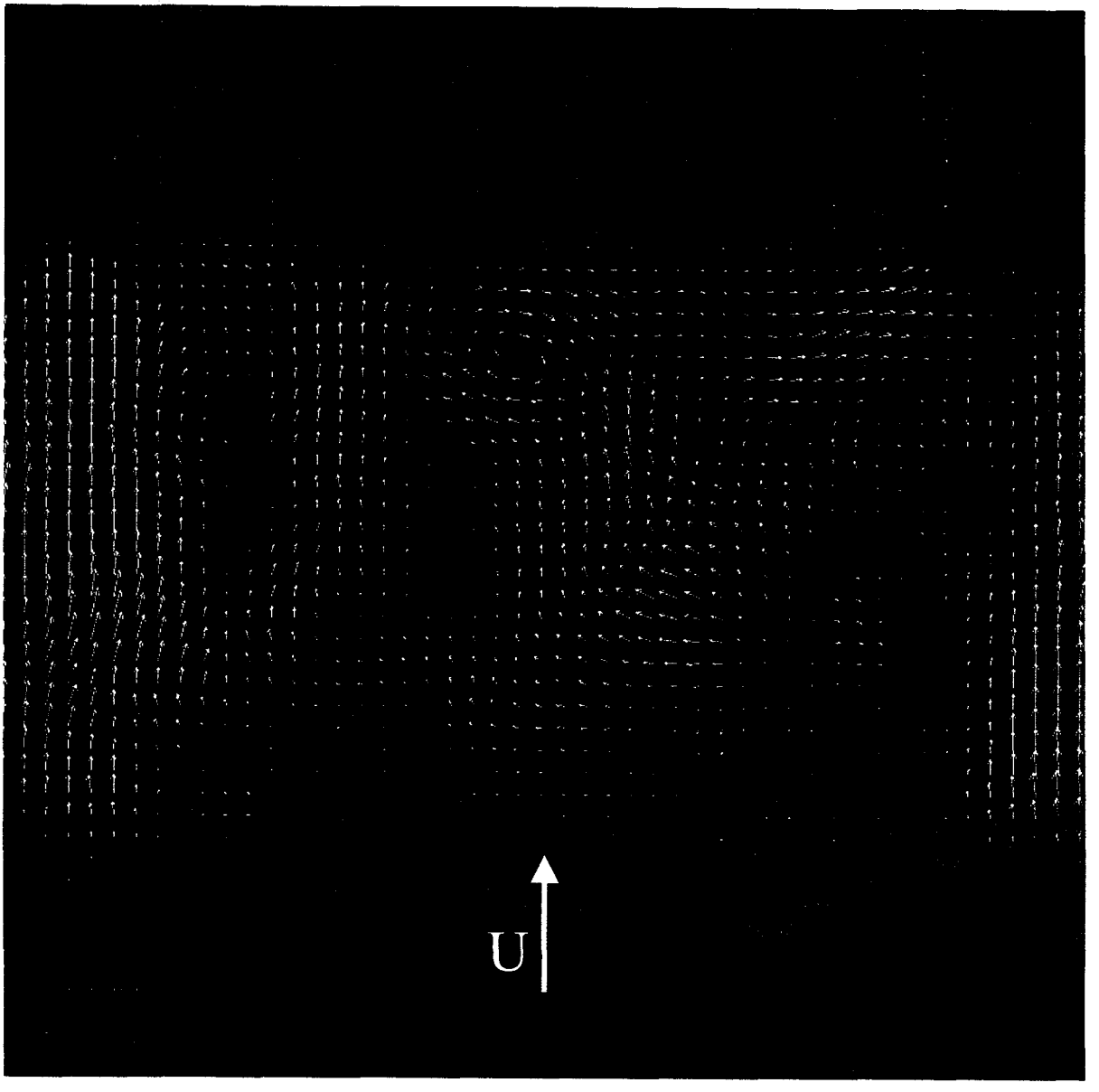
from: G.R. Spedding, "The evolution of initially turbulent bluff-body wakes at high internal Froude number" JFM 337 (1997)

Vans in back-to-back configuration

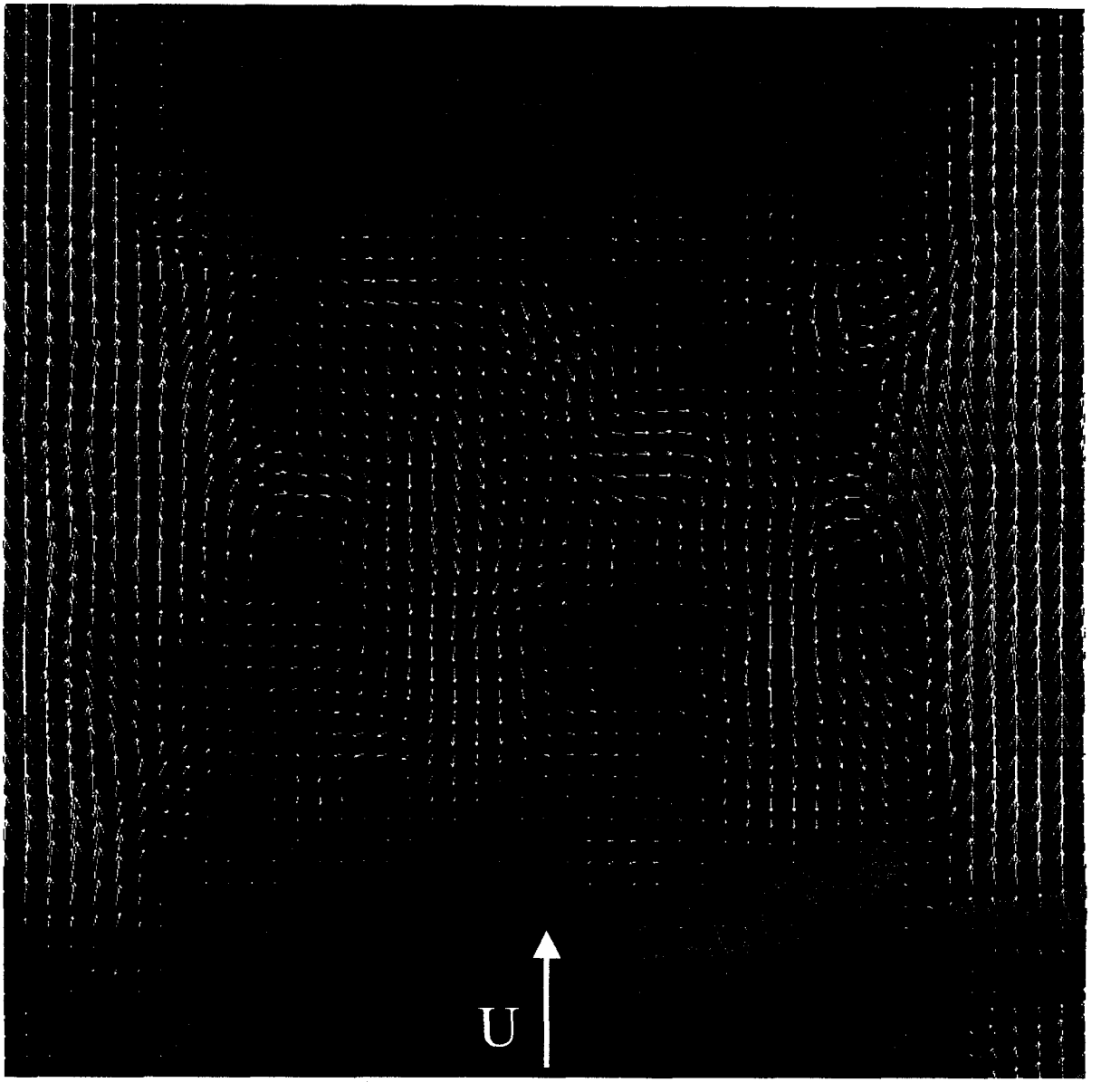


Van dimensions	L=25", H=8"
Free-stream velocity	25 m/s
Horizontal planes	28%, 46%, 65%, 84% of H
Vertical plane	Centerline
Spacing	D/L=23% and 6%
Seeding	One-micron droplets
Illumination	Two Nd-Yag lasers, 160 mJoule/pulse
Acquisition rate	10 Hz
Camera	1000 x 1000 pixels, dual channel CCD
Image processing	CIV/USC

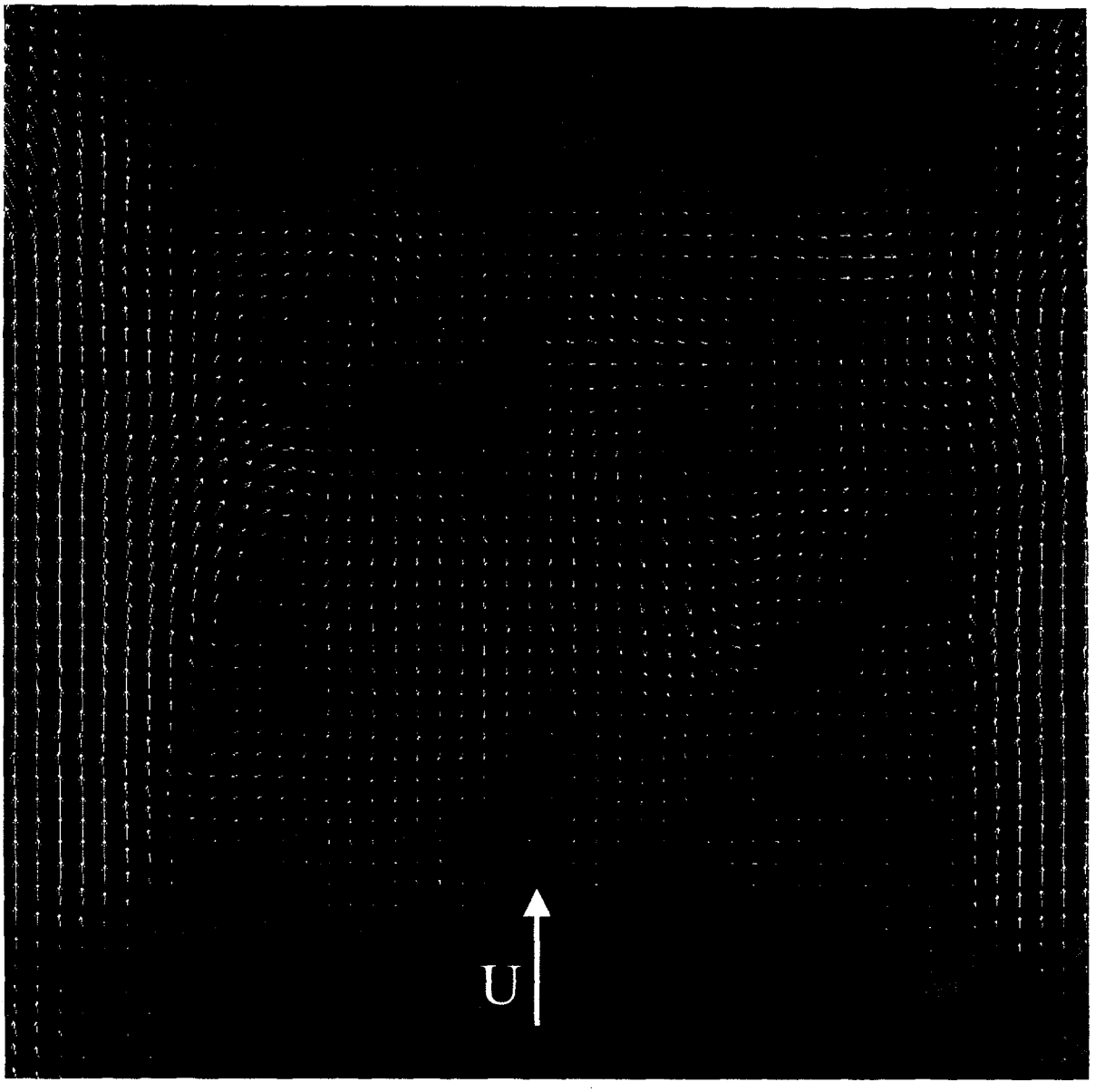
Velocity field for D/L=23%
Horizontal plane at Z/H=0.28



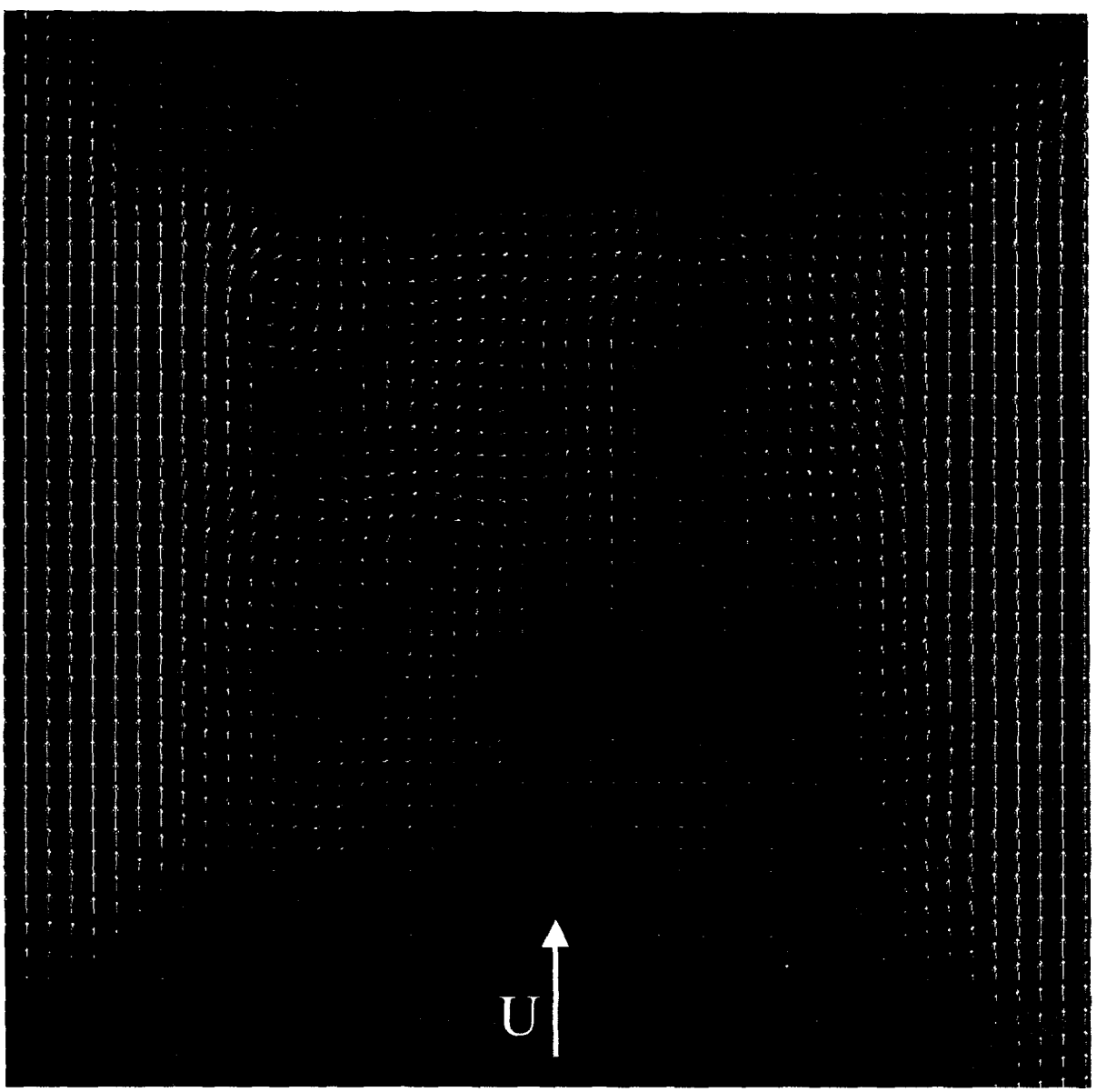
Velocity field for D/L=23%
Horizontal plane at Z/H=0.46



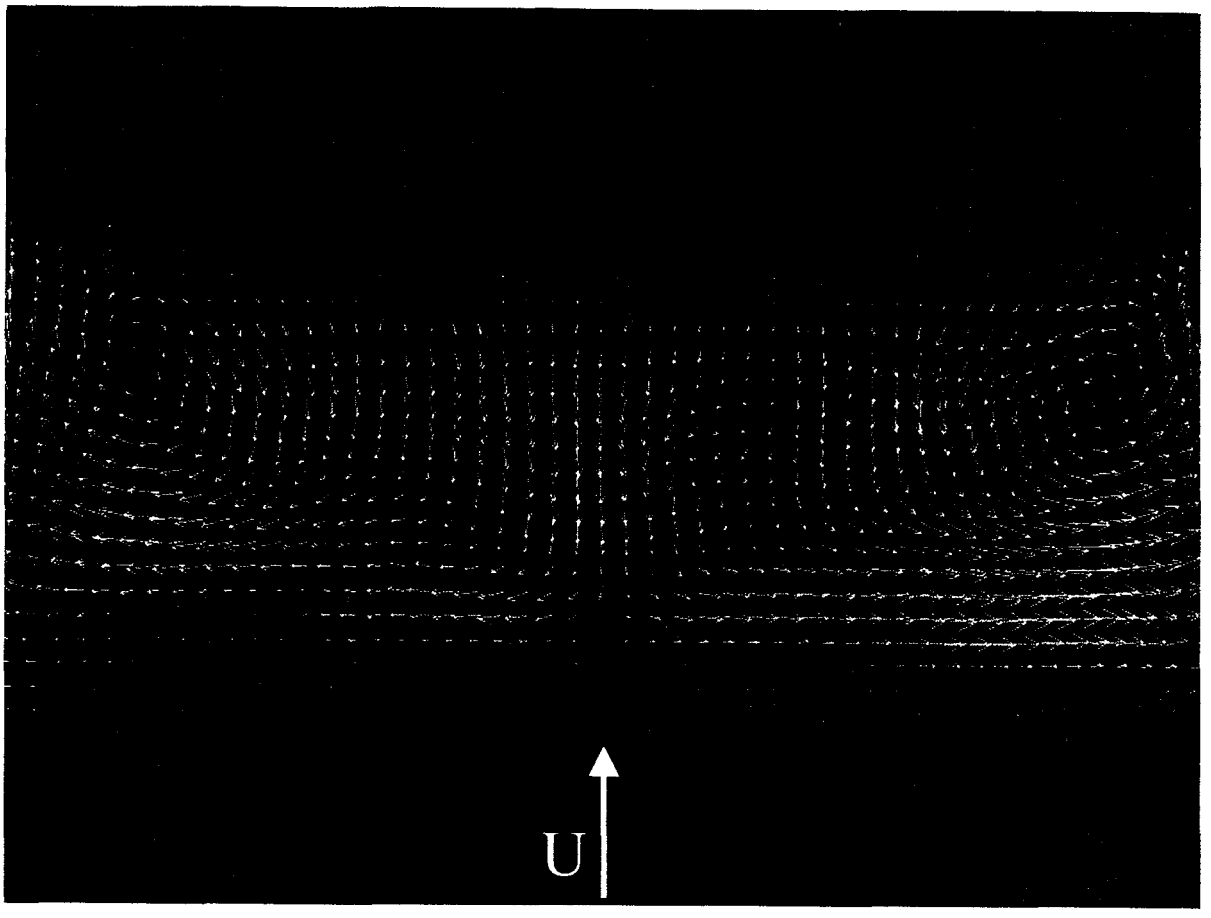
Velocity field for D/L=23%
Horizontal plane at Z/H=0.65



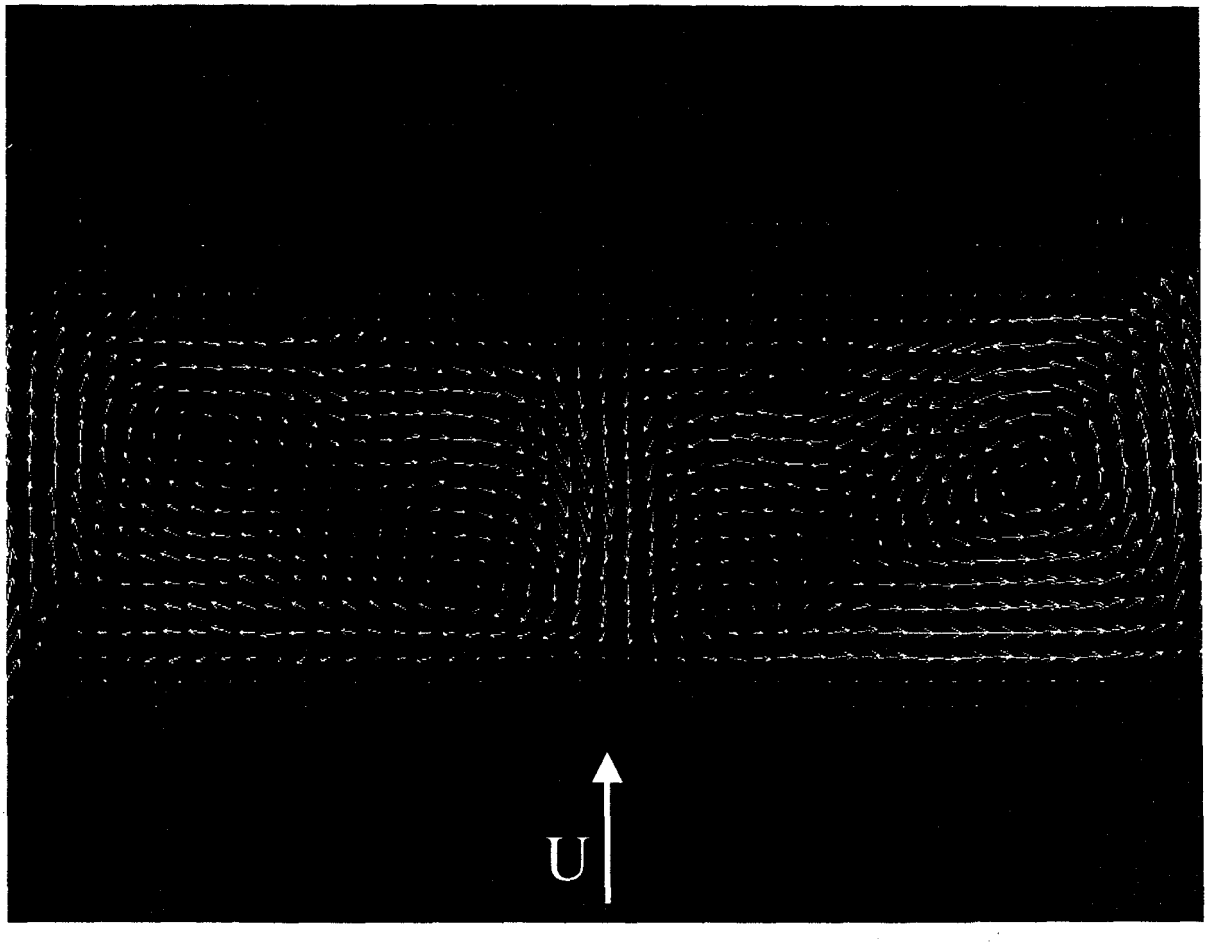
Velocity field for D/L=23%
Horizontal plane at Z/H=0.84



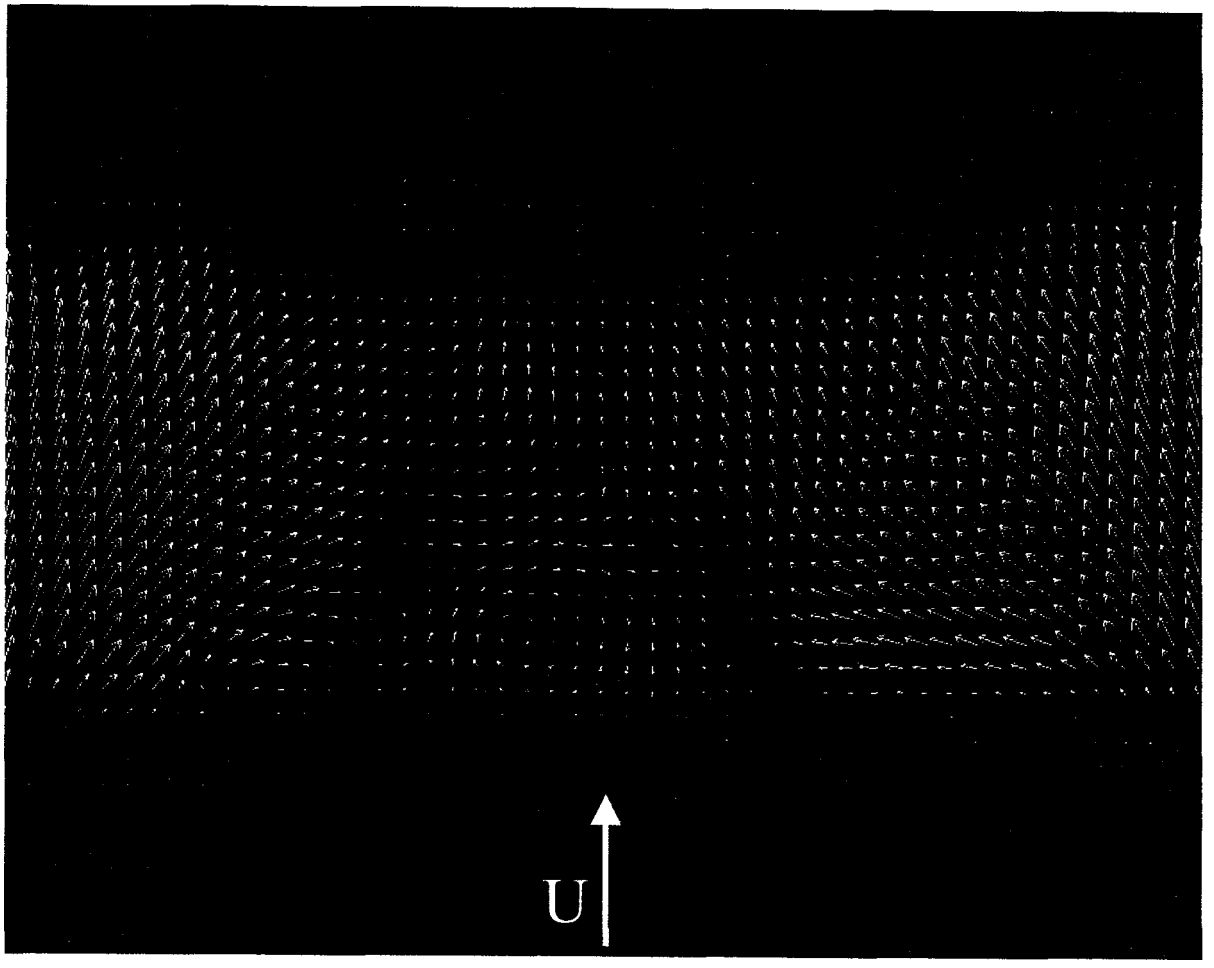
Velocity field for D/L=6%
Horizontal plane at Z/H=0.46



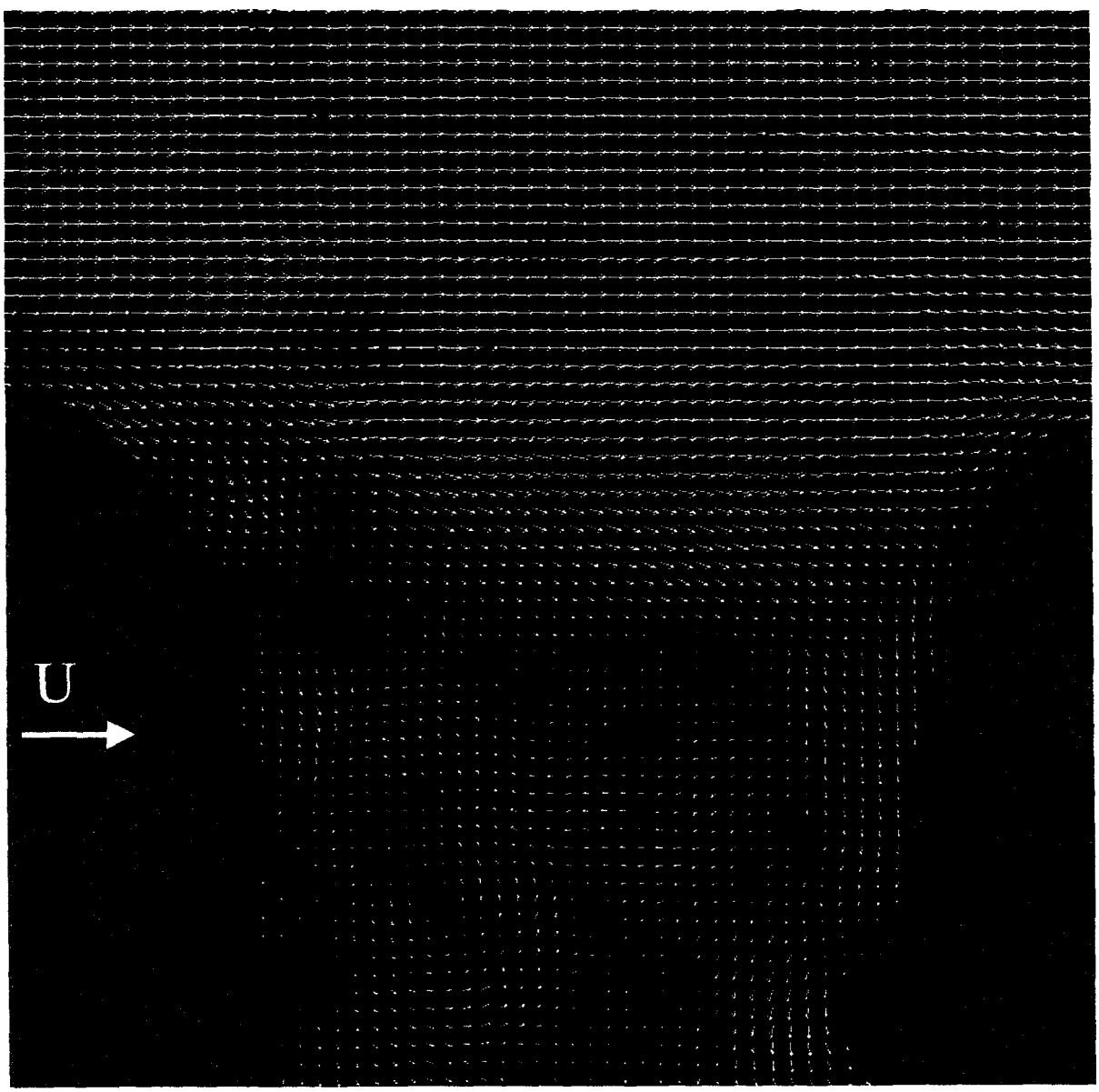
Velocity field for D/L=6%
Horizontal plane at Z/H=0.65



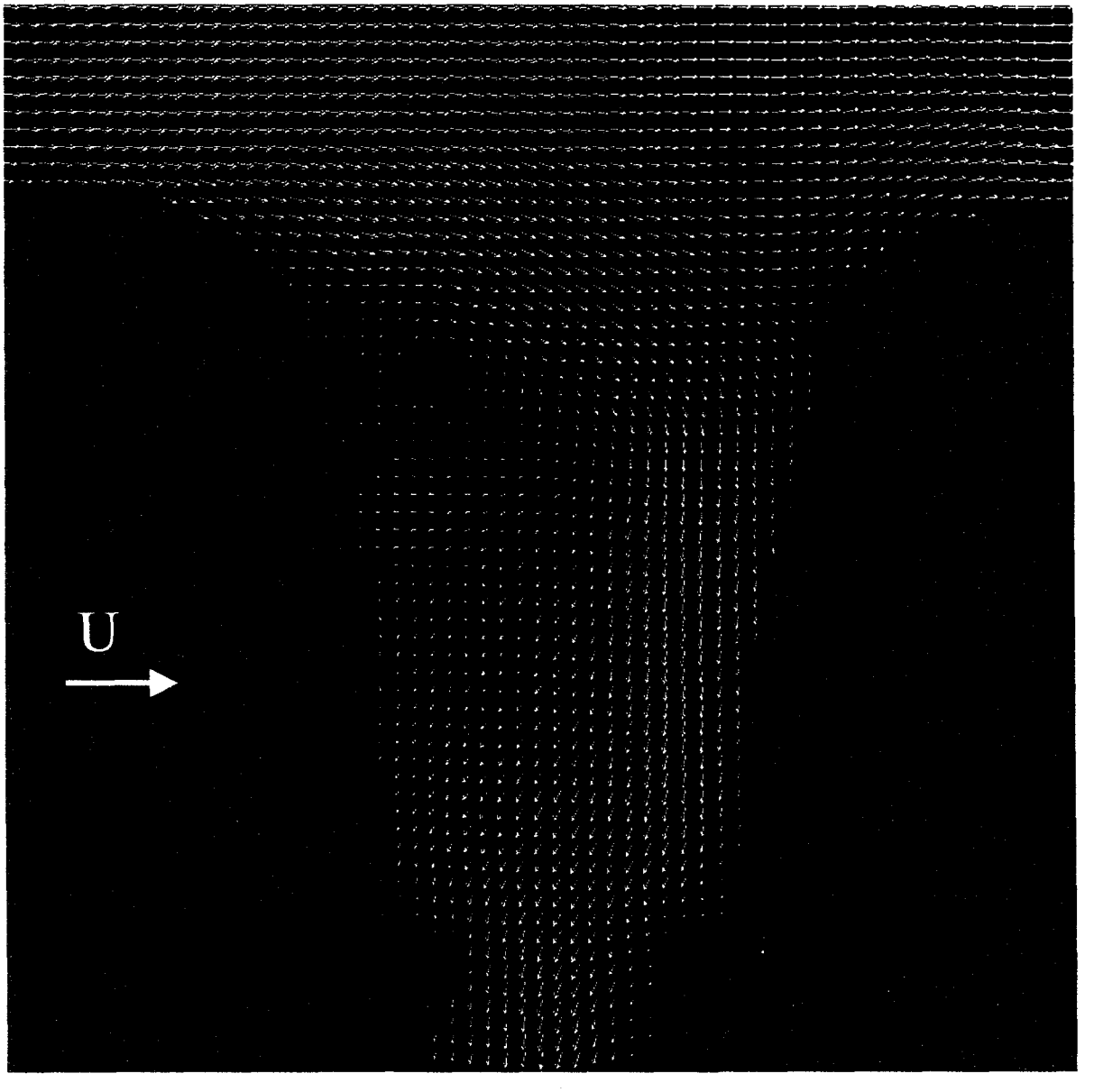
Velocity field for D/L=6%
Horizontal plane at Z/H=0.84



Instantaneous velocity field
Vertical mid-plane, D/L=23%



Instantaneous velocity field
Vertical mid-plane, D/L=6%



Aerodynamic Design of Heavy Vehicles

Overview of the Computational Plans (RANS, LES)

Kambiz Salari

Aerosciences and Compressible Fluid Mechanics Dept. 9115

Sandia National Laboratories

March 1999

Sandia National Laboratories

Projected Sandia Milestones, FY99-FY01

Sandia National Laboratories

Engineering Sciences Center

FY99

- High Reynolds number RANS calculations
- Comparison with Texas A&M 7x10 test
- Begin working with NASA/ARC 7x10 test
- Initiate tractor-trailer gap and height mismatch study
- Initiate incorporation of LES into SACCARA

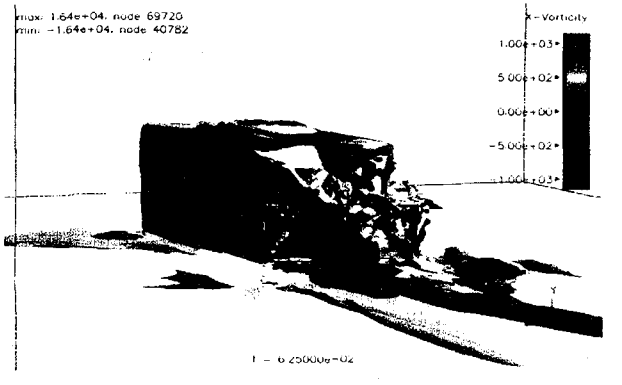
RANS calculation of GTS geometry

FY00

- Comparison with NASA/ARC 7x10 test
- Initiate RANS validation process
- Continue with incorporation of LES into SACAARA and perform sample calculations
- Initiate calculations for the tractor-trailer with gap and height mismatch

FY01

- Continue with RANS validation
- Continue with LES computation
- Continue with gap/height mismatch calculations
- Initiate LES validation



Demo LES calculation of Ahmed geometry

GTS Flow Simulation

Ground Transportation System (GTS) vehicle

Texas A&M 7'x10' low speed tunnel test

Test condition:

Run = 31, Re = 1.6×10^6, Wheels removed

Yaw angle = 0, 10 (deg.)

Free stream velocity = 78 (m/s)

Density = 1.17 (kg/m^3)

Static pressure = 99,470.6 (Pa)

Kinematic viscosity = 1.555×10^{-5} (m^2/s)

Matrix for Grid Convergence Study

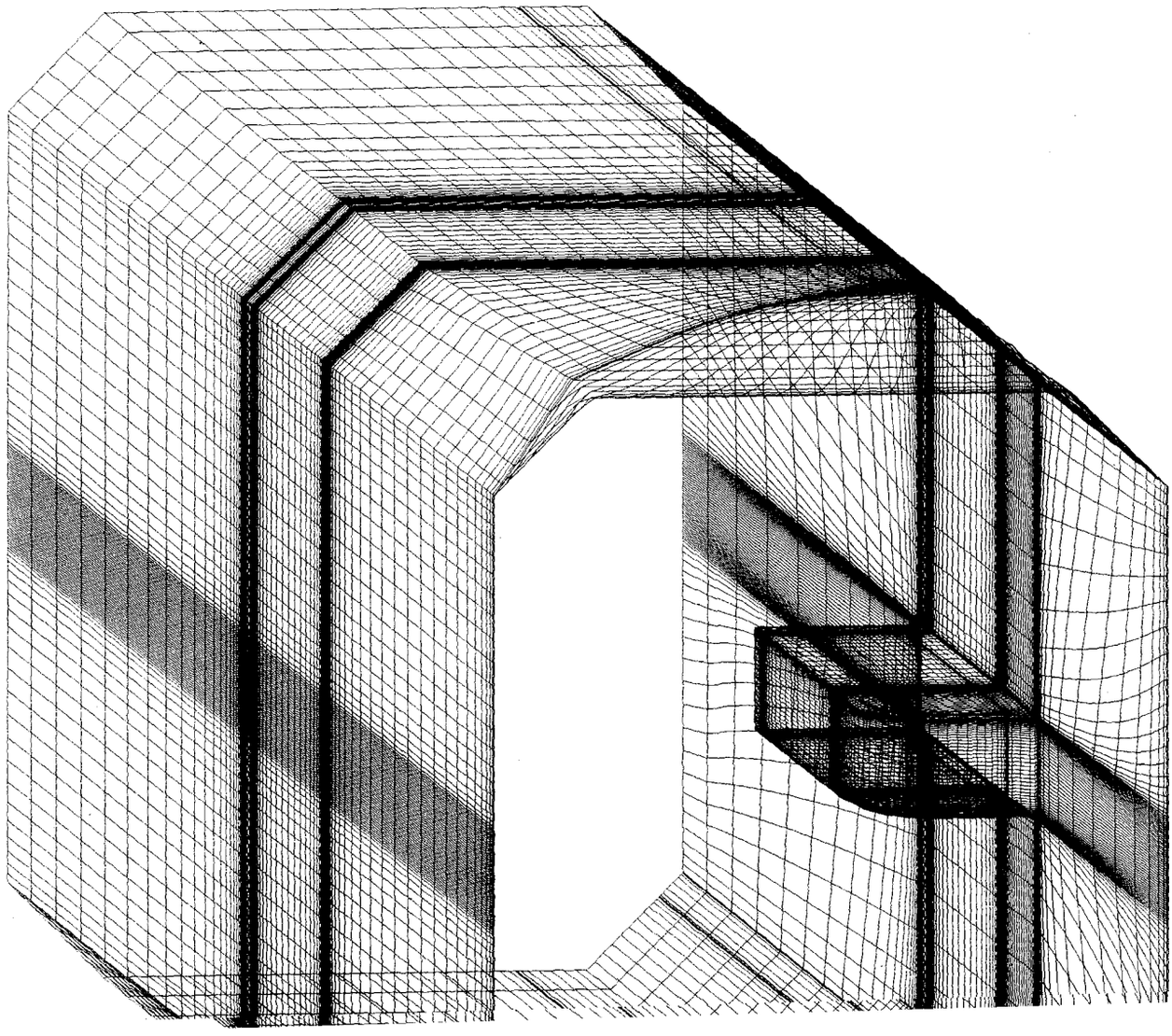
Yaw Angle	Grid Size		
	Coarse	Medium	Fine
0	X	X	
10	X	X	

Coarse Mesh: 0.5 million nodes, 107 processors

Medium Mesh: 4 million nodes, 246 processors

Fine Mesh: 32 million nodes, 1414 processors

All calculations were performed on TeraFlop ASCI Red machine



GTS Flow Simulation

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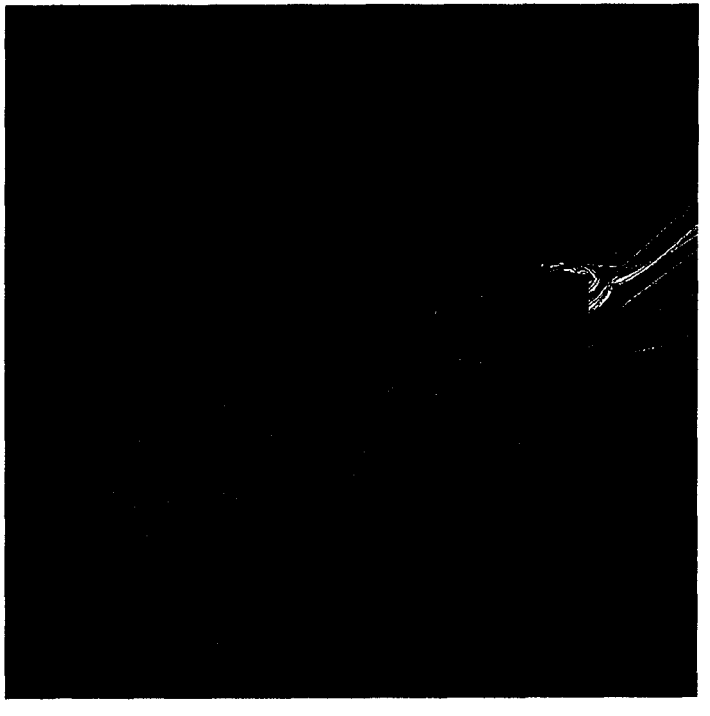
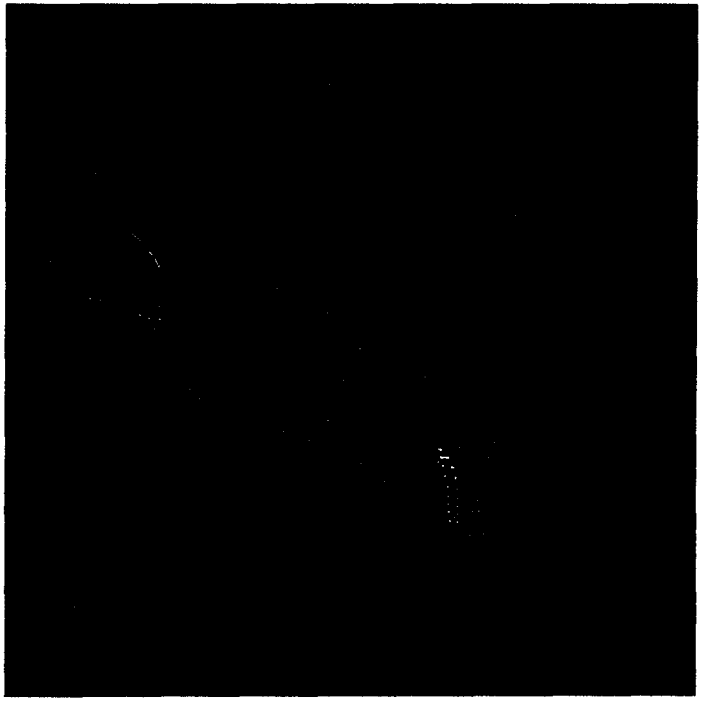
Engineering Sciences Center

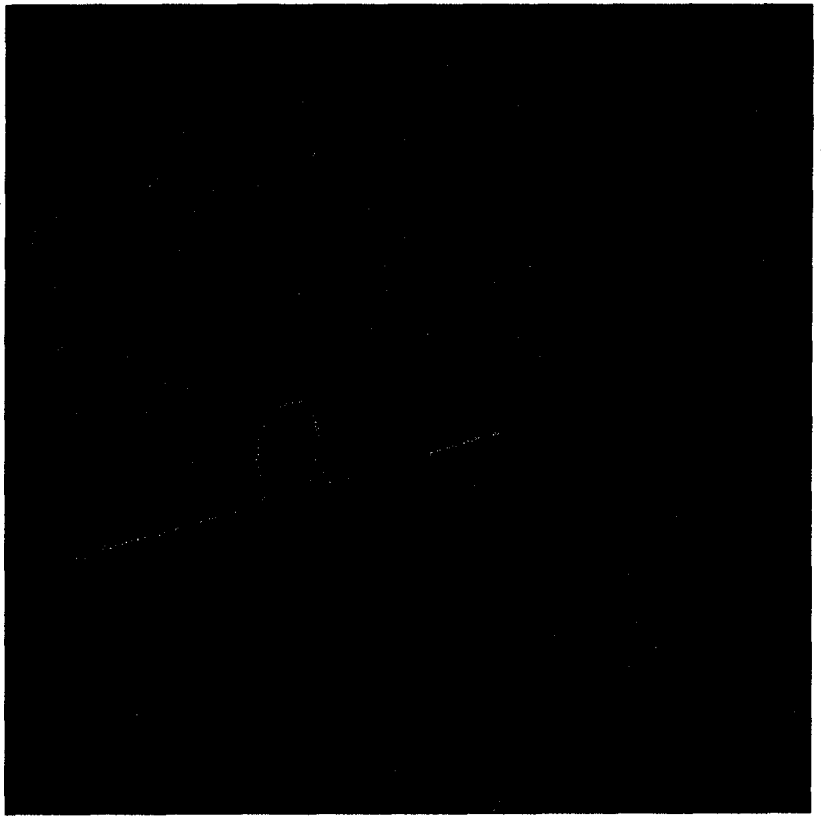
10 degrees yaw angle





GTS Flow Simulation

0 degrees yaw angle
x-plane cut
Mach contours



GTS Flow Simulation

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Engineering Sciences Center

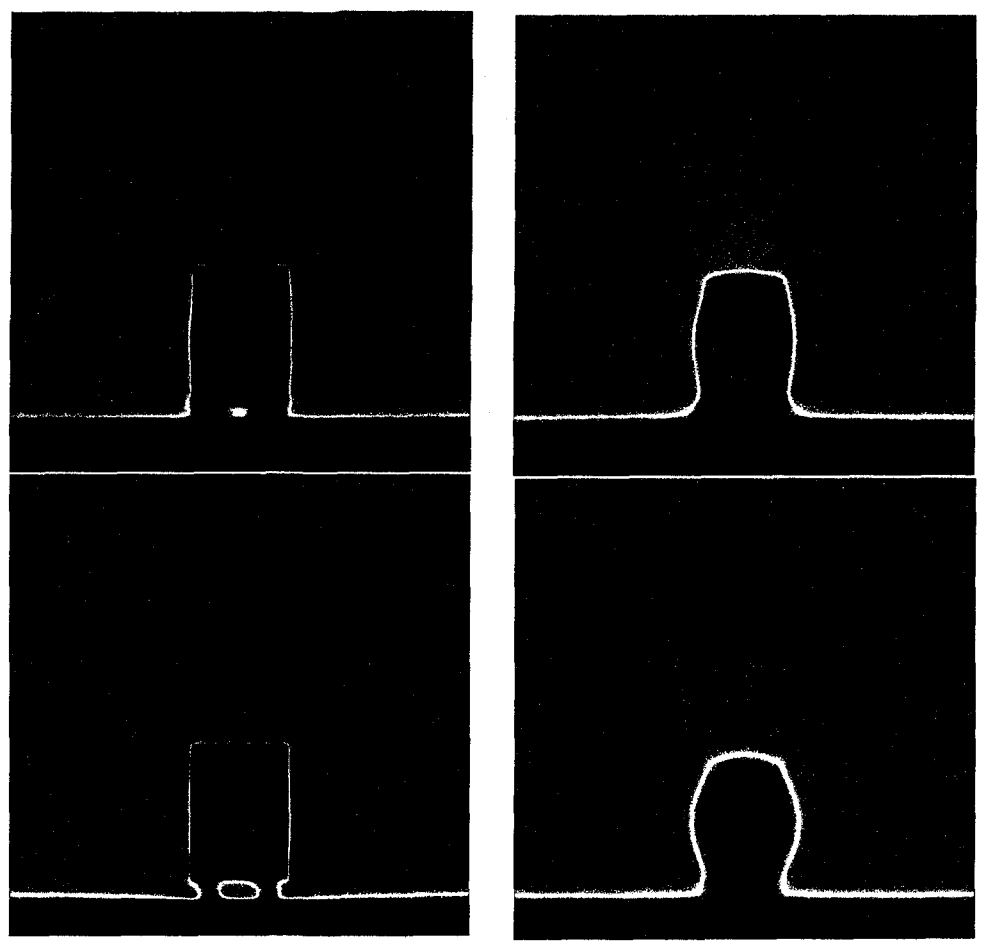
0 degrees yaw angle
x-plane cut
Mach contours

x = 2.5 meters

x = 3.25 meters

Coarse

Medium

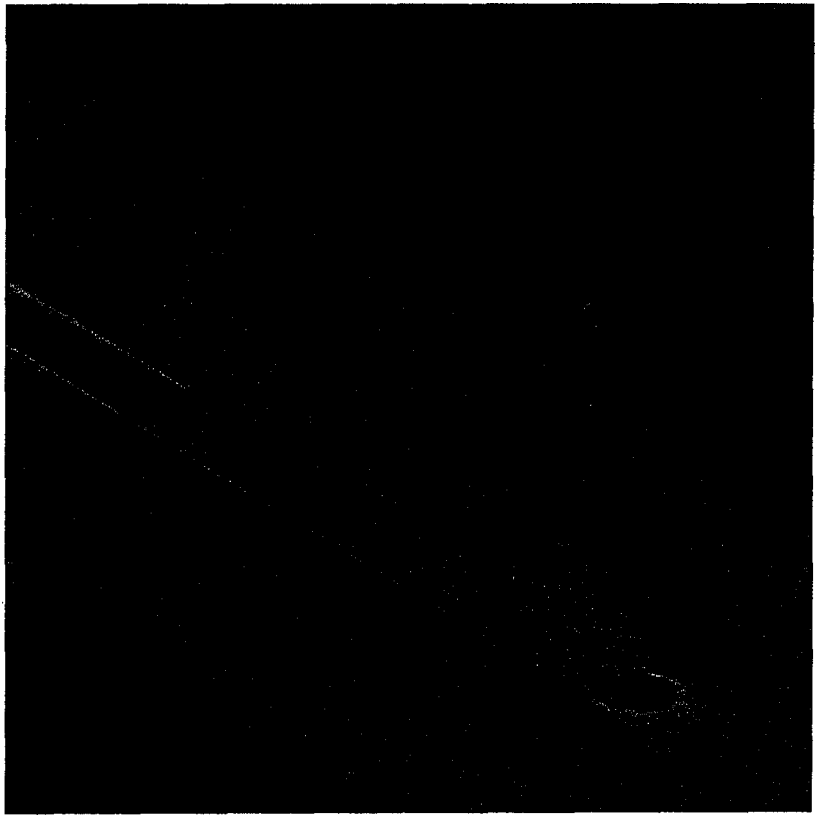


GTS Flow Simulation

Sandia National Laboratories

Engineering Sciences Center

0 degrees yaw angle
y-plane cut
Mach contours

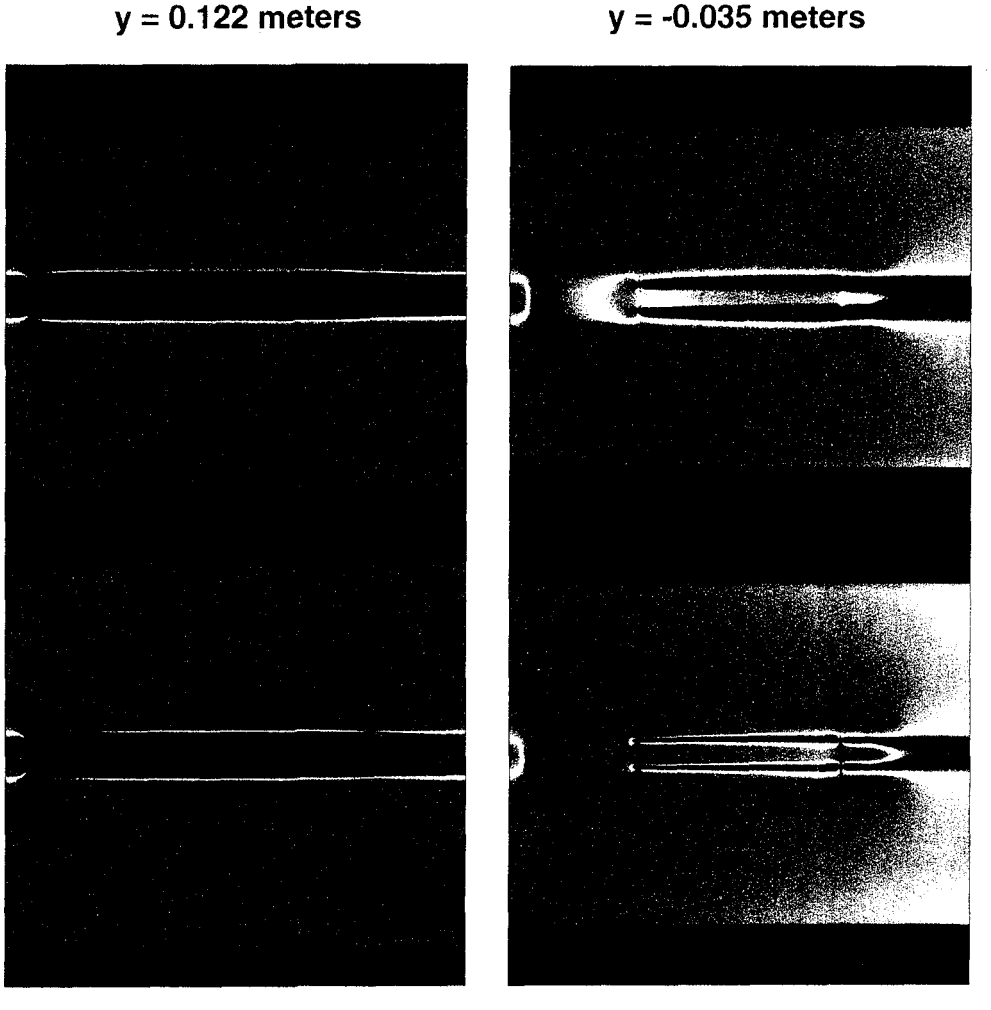


GTS Flow Simulation

Sandia National Laboratories

Engineering Sciences Center

0 degrees yaw angle
y-plane cut
Mach contours

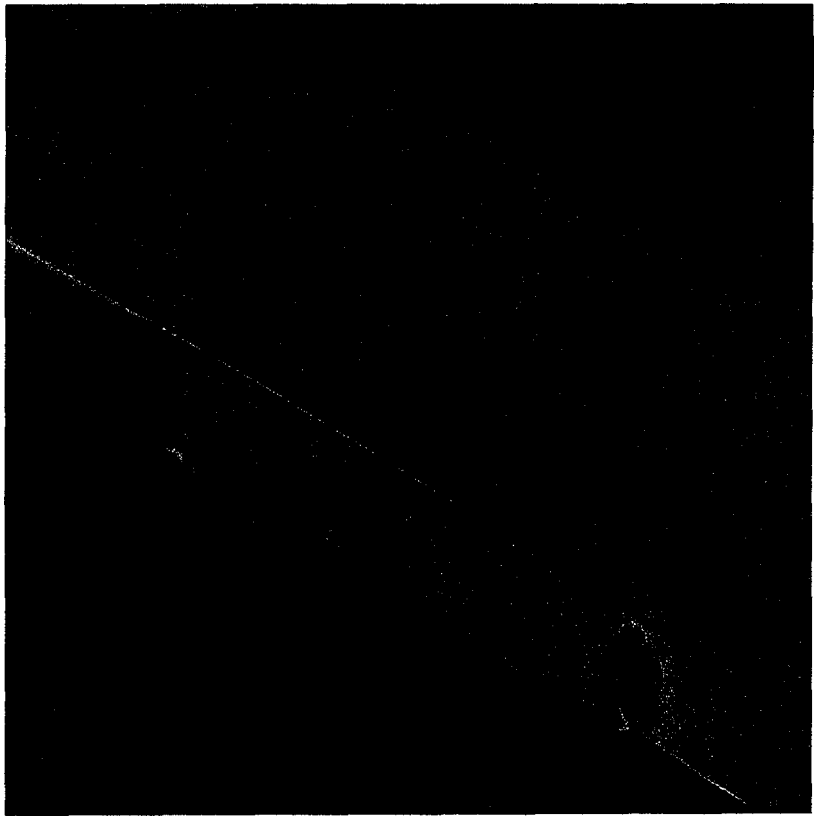


GTS Flow Simulation

Sandia National Laboratories

Engineering Sciences Center

0 degrees yaw angle
z-plane cut
Mach contours



GTS Flow Simulation

Sandia National Laboratories

Engineering Sciences Center

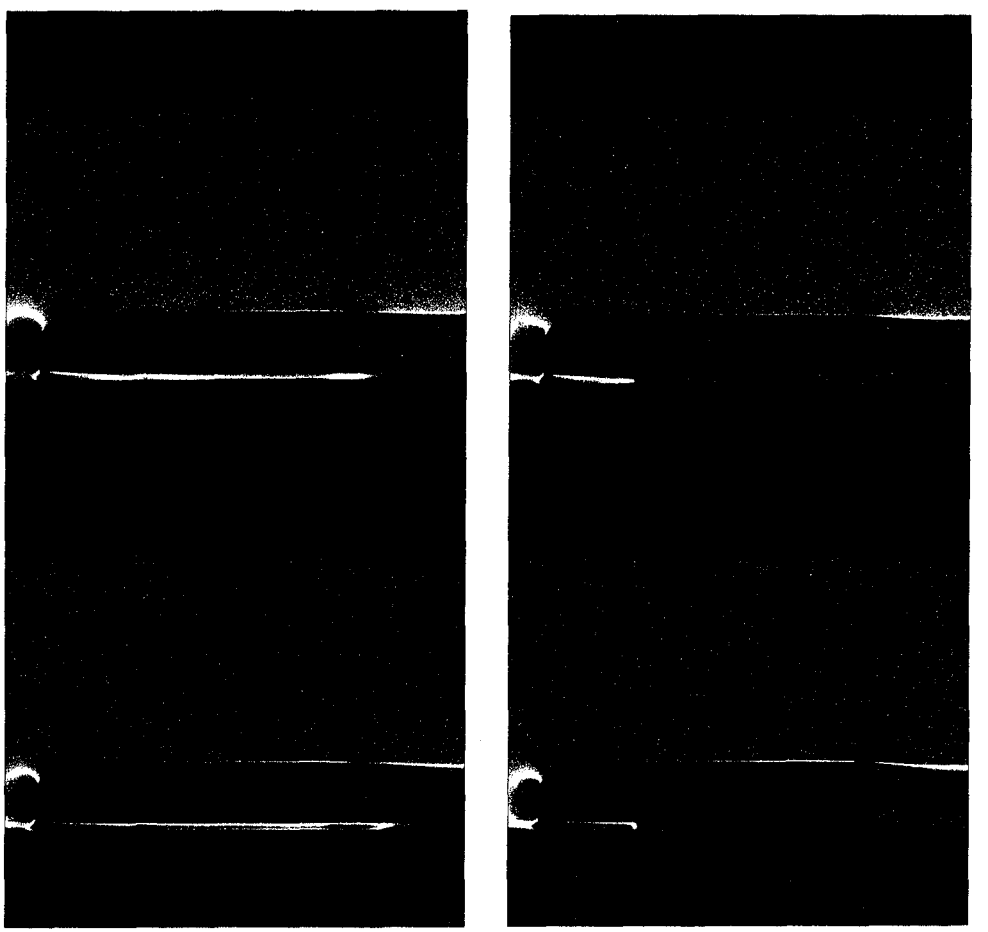
0 degrees yaw angle
z-plane cut
Mach contours

z = 0.0 meters

z = 0.1 meters

Coarse

Medium



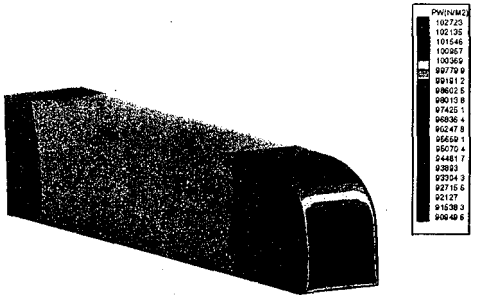
Pressure Distribution on the Surface
Coarse to Medium Grid Comparison

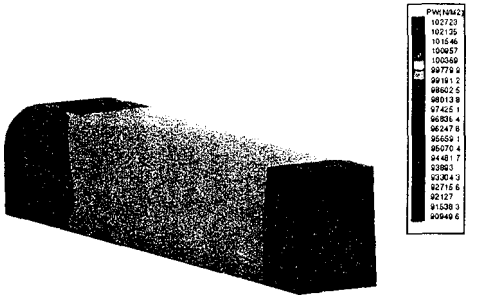
Sandia National Laboratories

Engineering Sciences Center

0 degrees yaw angle

Coarse





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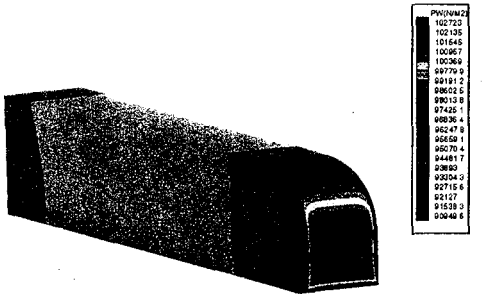
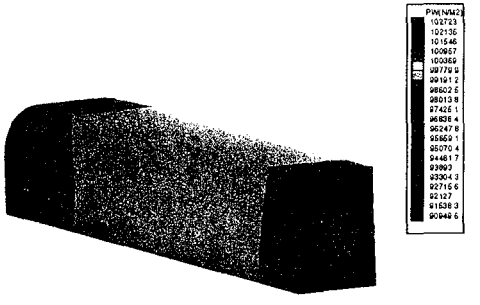




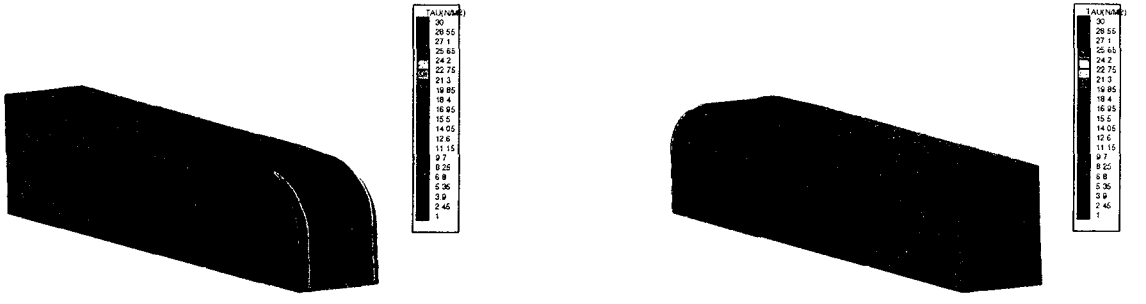
Shear Stress Distribution on the Surface
Coarse to Medium grid comparison

Sandia National Laboratories

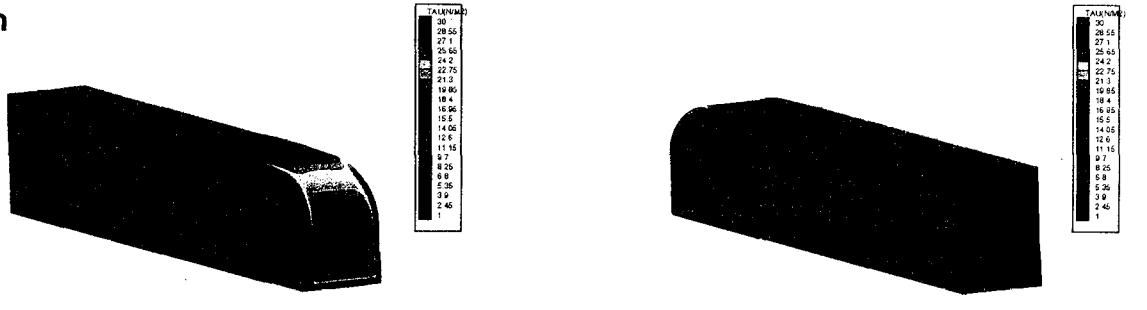
Engineering Sciences Center

0 degrees yaw angle

Coarse



Medium

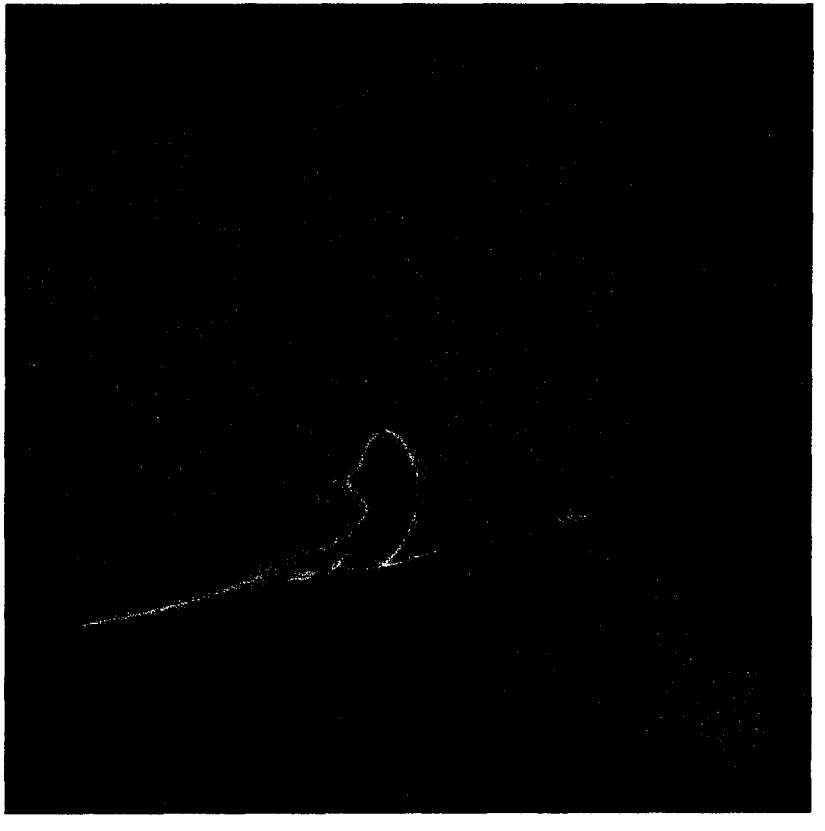


GTS Flow Simulation

Sandia National Laboratories

Engineering Sciences Center

10 degrees yaw angle
x-plane cut

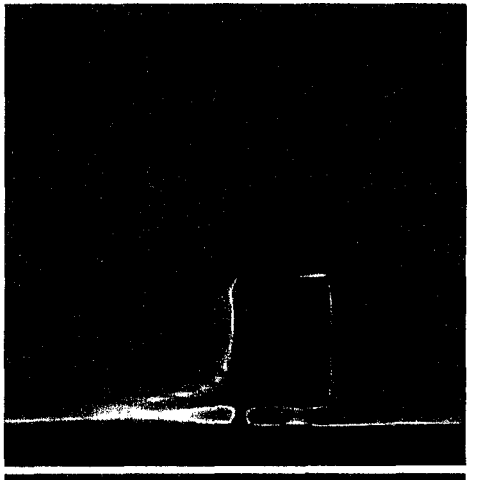
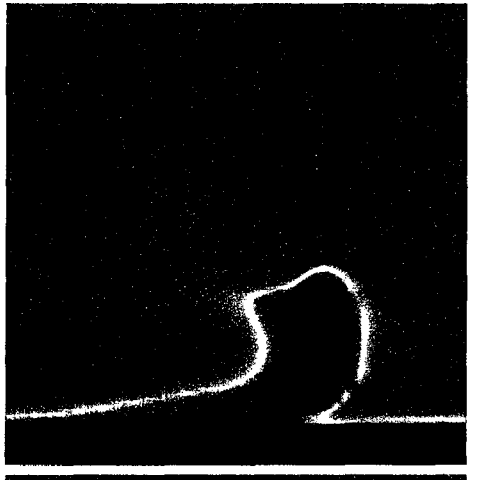
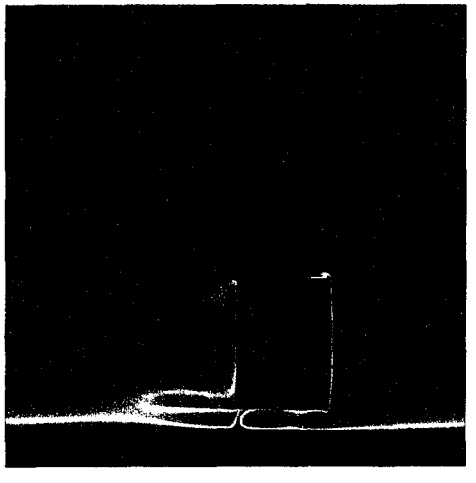
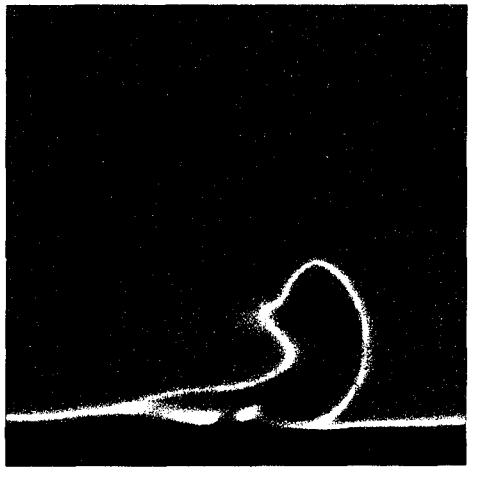


GTS Flow Simulation

Sandia National Laboratories

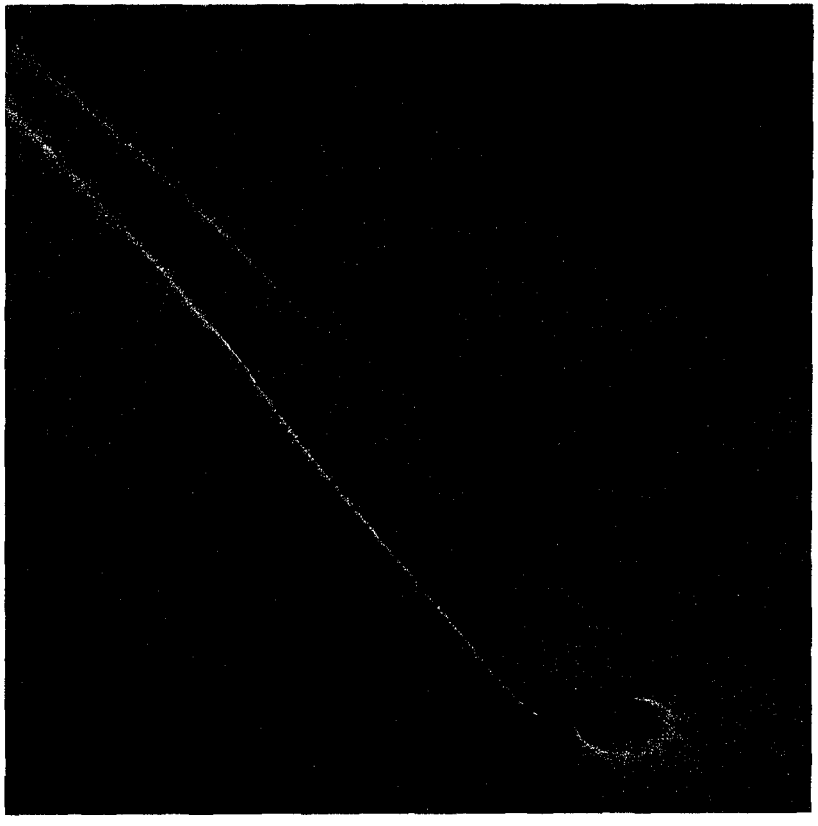
Engineering Sciences Center

10 degrees yaw angle
x-plane cut
Mach contours

	x = 2.5 meters	x = 3.25 meters
Coarse		
Medium		

GTS Flow Simulation

10 degrees yaw angle
y-plane cut

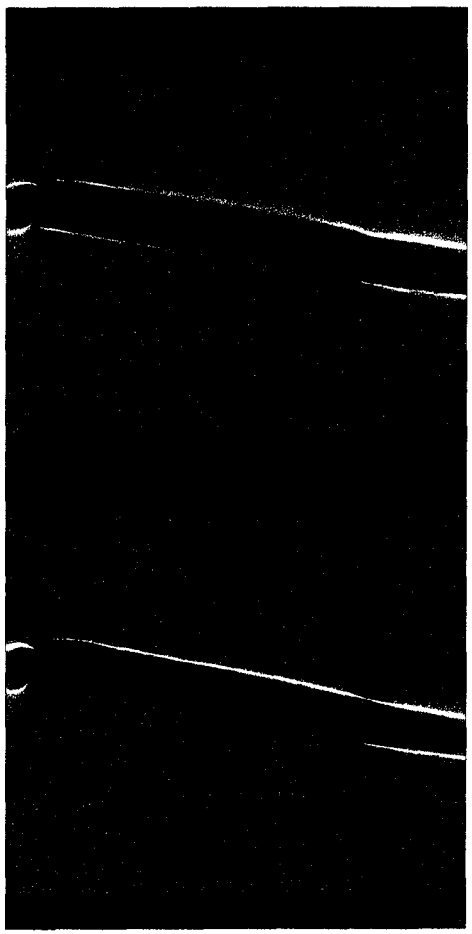


GTS Flow Simulation

Sandia National Laboratories

Engineering Sciences Center

10 degrees yaw angle
y-plane cut
Mach contours

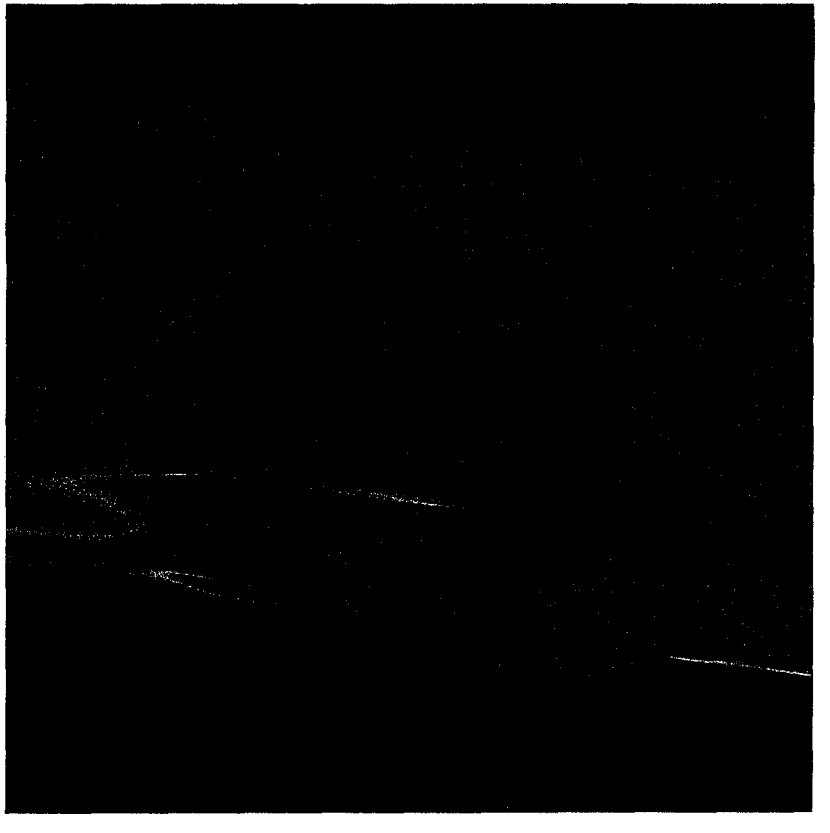
	y = 0.122 meters	y = -0.035 meters
Coarse		
Medium		

GTS Flow Simulation

Sandia National Laboratories

Engineering Sciences Center

10 degrees yaw angle
z-plane cut



GTS Flow Simulation

Sandia National Laboratories

Engineering Sciences Center

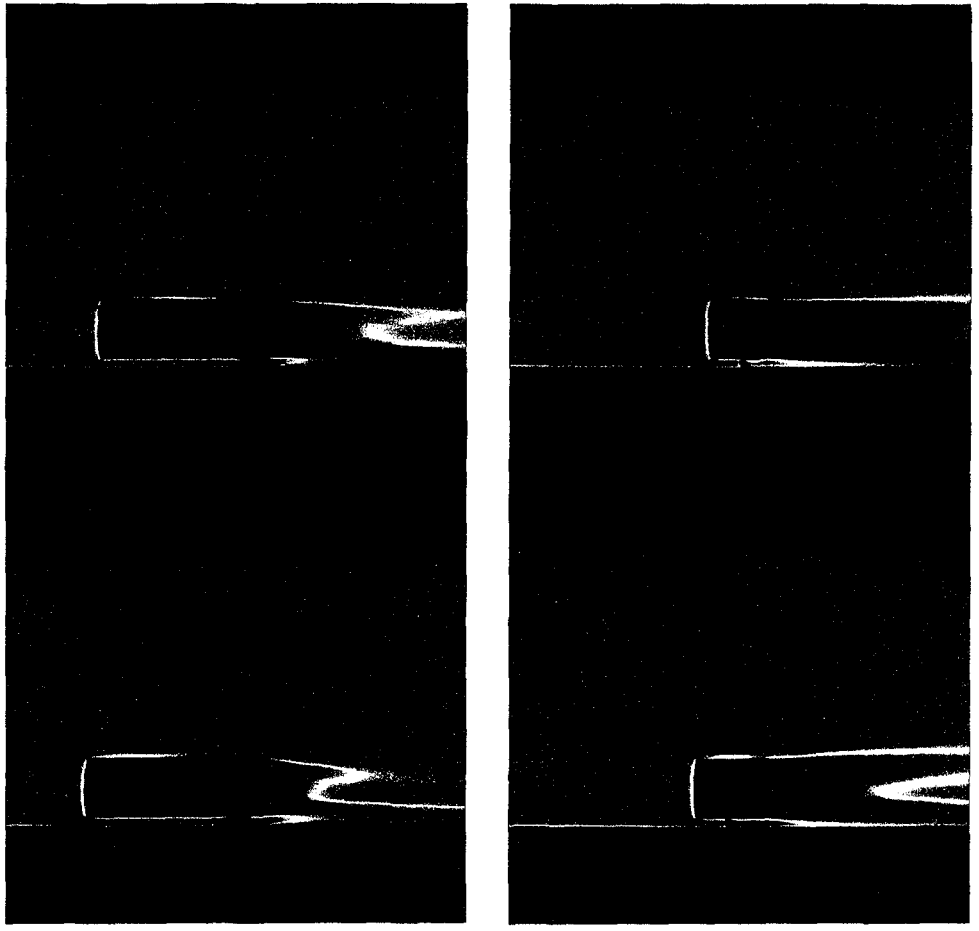
10 degrees yaw angle
z-plane cut
Mach contours

z = 0.07 meters

z = 0.215 meters

Coarse

Medium



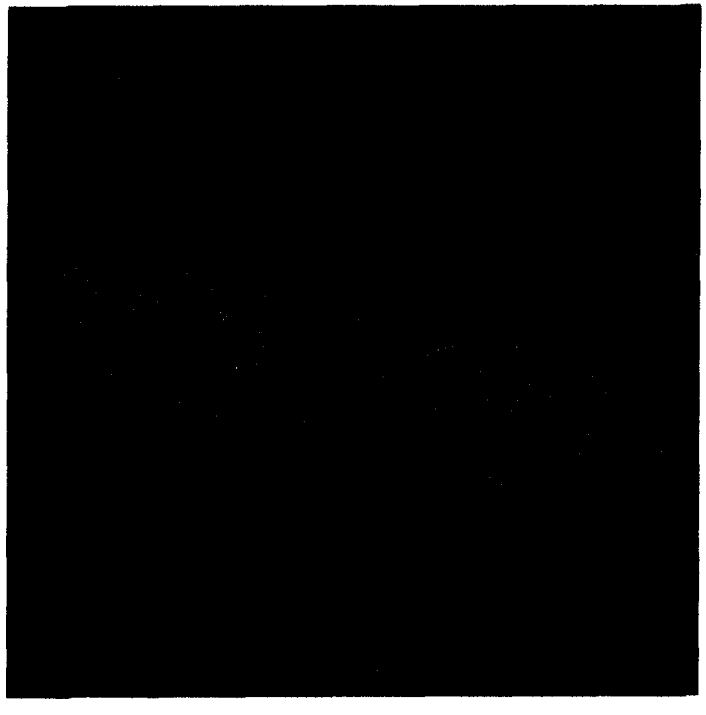
GTS Flow Simulation

Sandia National Laboratories

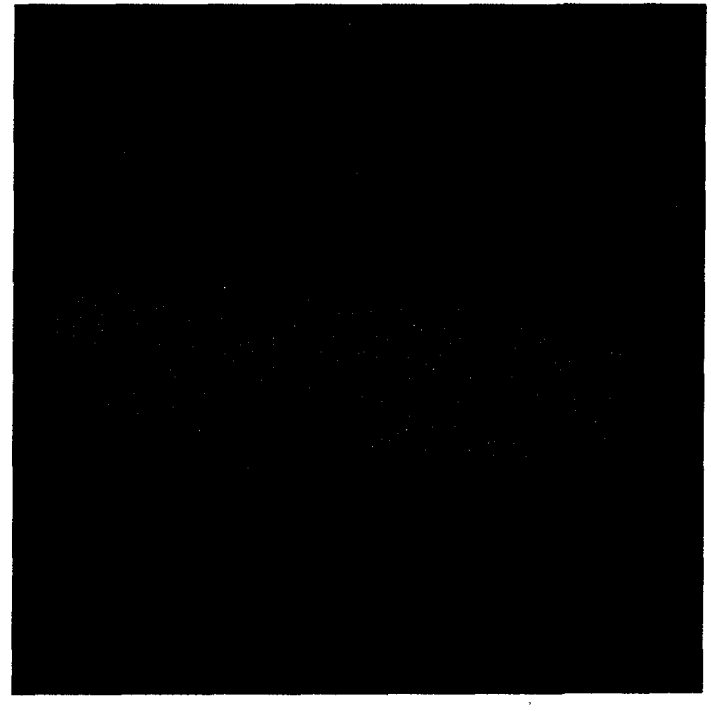
Engineering Sciences Center

10 degrees yaw angle
isoSurface u = -0.001 (m/s)

Coarse



Medium



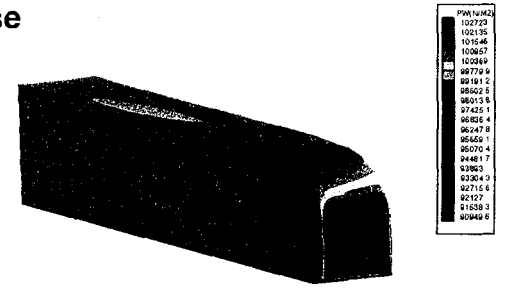
Pressure Distribution on the Surface
Coarse to Medium grid comparison

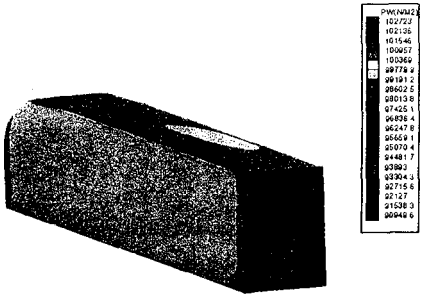
Sandia National Laboratories

Engineering Sciences Center

10 degrees yaw angle

Coarse





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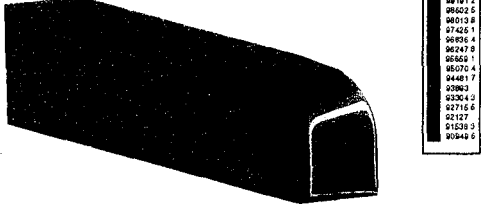
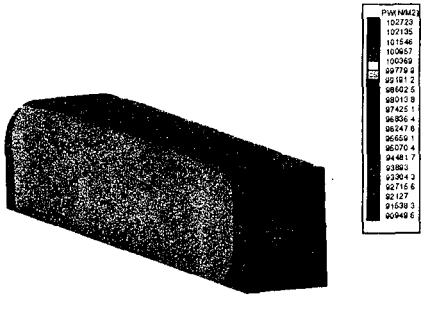




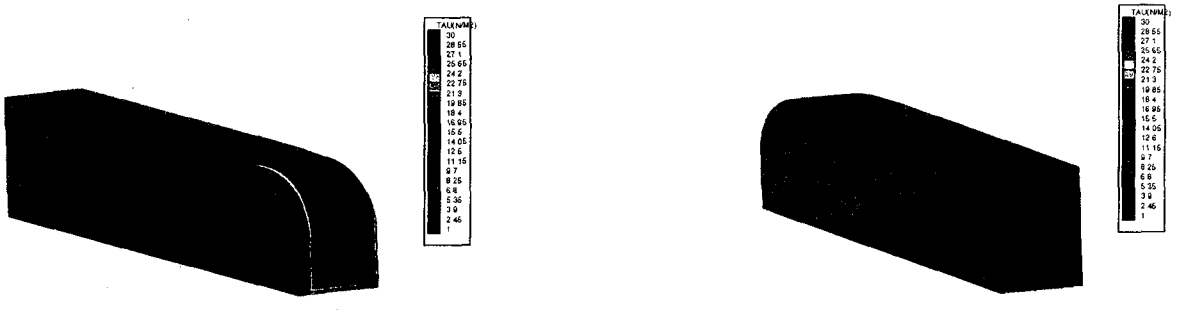
Shear Stress Distribution on the surface Coarse to Medium grid comparison

Sandia National Laboratories

Engineering Sciences Center

10 degrees yaw angle

Coarse



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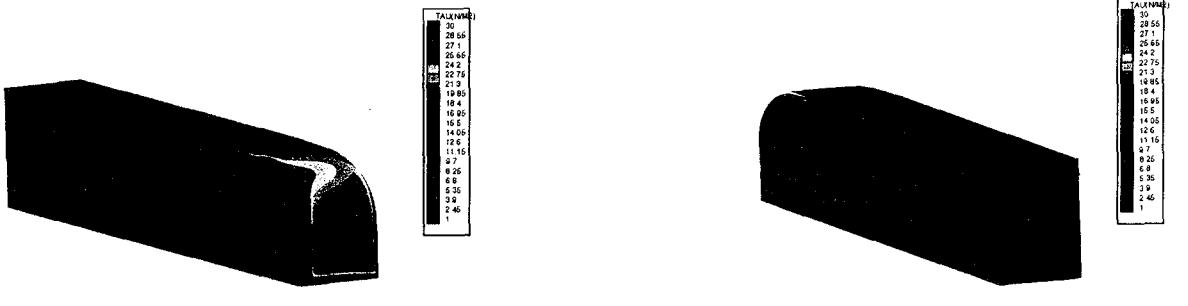


Flow Simulation Around Ahmed-Body GILA LES Computation (M. Christon)

Sandia National Laboratories

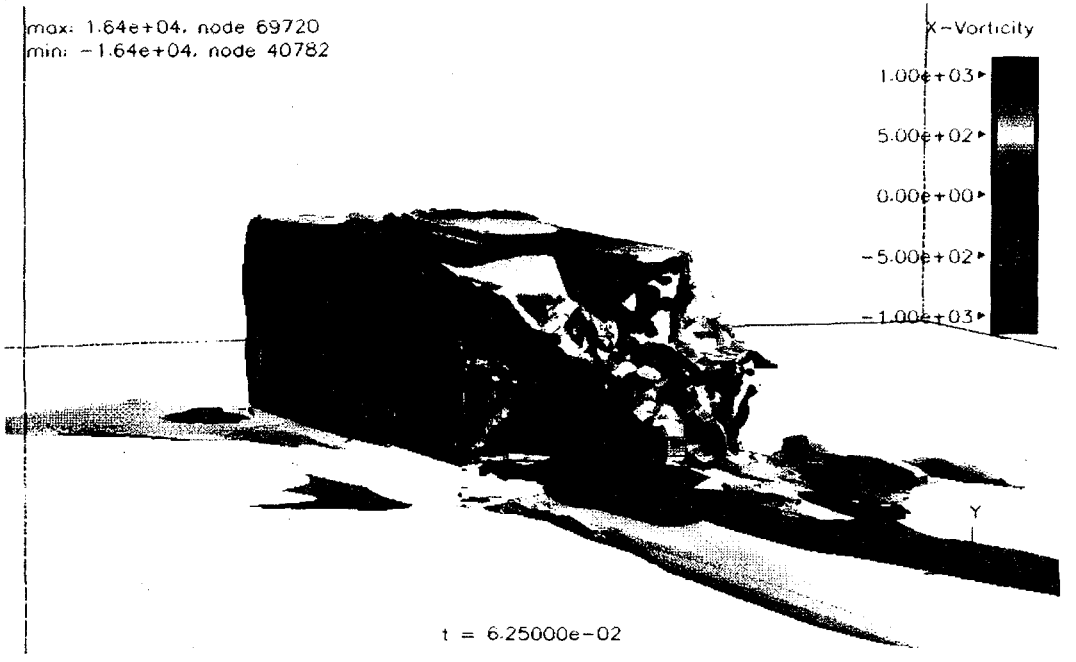
Engineering Sciences Center

Ahmed-body 30^o slant, $Re=4.29x10^6$

Experimental drag coefficient, $C_w = 0.378$

Predicted short time drag coefficient, $C_w = 0.386$

Grid size: about 800,000 elements, 128 processors



Projected Sandia Funding for FY00

Sandia National Laboratories

Engineering Sciences Center

	FY98	FY99			FY00		
		Low	High	Received	Low	High	Received
Old	$100K	$150K	$210K	$80K	$107K	$275K	
New					$177K	$345K	

FTE cost for FY98: $275K

FTE cost for FY99: $310K

FTE cost for FY00: $326K (Projected)

Truck Aerodynamics:

Large-Eddy Simulation (LES) using the Finite-Element Method (FEM)

Rose McCallen, Ph.D.
Lawrence Livermore National Laboratory

March 1999

University of California
Lawrence Livermore
National Laboratory

We need advanced CFD tools to accurately predict drag effects for trucks.

Flow is time dependent, 3D with a wide range of scales

- **Flapping recirculation zones**
- **Thin boundary layers transition and separate**
- **Flow tripped by head lamps, grab handles, etc.**
- **Everything upstream effects what happens downstream**

To reduce experimentation, accurate CFD with less empiricism is needed

- **Commercial CFD tools do not predict correct drag effects - per Industry**
- **Models have adjustable empirical parameters**

Chosen approach

- **Large-eddy simulation (LES) using the finite element method (FEM)**

LES is a challenge but we have the experience and resources to succeed.

Outline

Background

- Approach
- Challenges

Plan and Progress

- Formulation and implementation
- Benchmarking
- Truck simulation

Current Technology

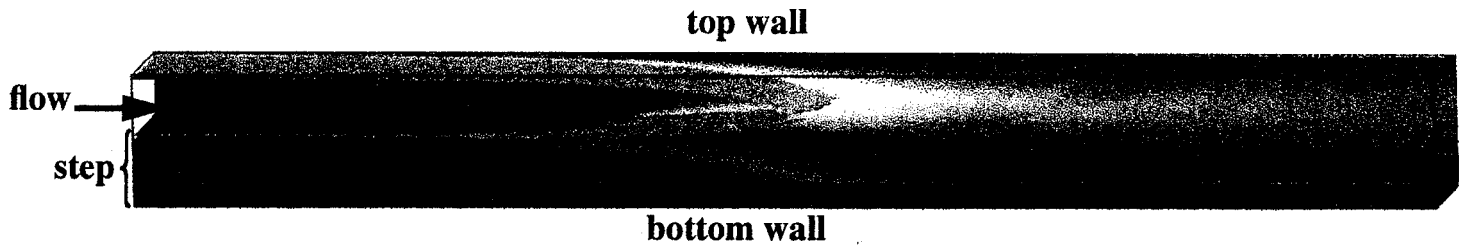
- RANS/LES hybrid - paper review

Large-eddy simulation provides a wealth of information and less empiricism.

Reynolds-averaged Navier-Stokes (RANS)

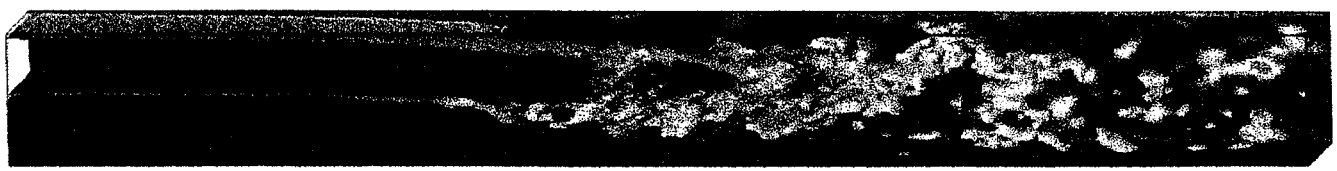
- **Many empirical parameters**
- **Time-averaged solution**

Backward-facing step: streamwise velocity



Large-eddy simulation (LES)

- **One empirical parameter -> less empiricism**
- **3D, unsteady solution of vortex shedding**



The LES challenges are related to physical as well as numerical modeling.

Boundary layers are too thin	**Can't resolve boundary layers - problem gets too big**
	Wall approximations in development
Runtime too long	**Evolution is over long time scales**
	Parallel computations/solvers required - in development
Analysis	**Huge data sets**
	Visualization required - in development
	Methods for testing convergence (V&V) in development

Significant development being done by LLNL programs.

The first year deliverable is to 'integrate' and develop the flow model and complete a demonstration problem.

Milestone — FY99 incompressible flow demonstration

R&D
- Solver integration/parallelization
- Turbulence modeling
- Boundary conditions
- Data analysis

Approach

Utilize existing methods, tools, resources, etc. (keep it simple)
- Existing/tried formulation
- Smagorinsky SGS model for FY99
- Integrating existing codes

Take advantage of the Lab's infrastructure (keep it simple)

For the incompressible flow modeling we are taking advantage of existing methods and codes.

ALE3D
structural/thermal/chemistry/compressible-flow

Incompressible LES/FEM Code

Tasks	Status
Establish compatibility and flexibility of the formulation	✓
Extract physics coding from existing code and modify for ALE3D	✓
Establish parallelization approach and implement	in progress
Coding for input/output and postprocessing issues	in progress
Benchmark testing	

The formulation is an established method, but solver implementation 'was' an issue.

Formulation, solution approach, and coupling

$$\boxed{(C^T M^{-1} C)P^n = C^T A^n}$$

← **Solve for pressure**

where $A^n = M^{-1}[(K^n + N(u^n))\underline{u}^n - F(u^n)]$

$$\underline{u}^{n+1} = \underline{u}^n - \delta t(A^n - M^{-1} C P^n)$$

← **Update velocity**

where

$$C = \begin{bmatrix} c_{in(1)} \\ c_{in(2)} \\ c_{in(3)} \end{bmatrix}; c_{in(\alpha)} = \int_\Omega \psi_n \frac{\partial \phi_i}{\partial x_\alpha} \quad M = \begin{bmatrix} m_{ij} & 0 & 0 \\ 0 & m_{ij} & 0 \\ 0 & 0 & m_{ij} \end{bmatrix}; m_{ij} = \int_\Omega \phi_i \phi_j$$

← **$C^T M^{-1} C$ is only a function of geometry**

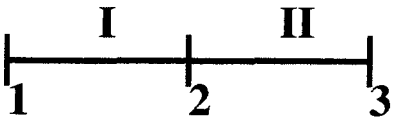
Matrix characteristics and solver

- **Piecewise constant pressure basis functions ('zone centered')**
- **Setting-up a row at a time!**

← **Can't use solver's Finite Element Interface (FEI)**

The $C^T M^{-1} C$ matrix is *global* and can't be constructed element-by-element.

One-Dimensional Example



$$(C^T M^{-1} C)P = rhs$$

$$\begin{bmatrix} c_{1I} & c_{2I} & 0 \\ 0 & c_{2II} & c_{3II} \end{bmatrix} \begin{bmatrix} m_{1I} & 0 & 0 \\ 0 & (m_{2I}+m_{2II}) & 0 \\ 0 & 0 & m_{3II} \end{bmatrix} \begin{bmatrix} c_{1I} & 0 \\ c_{2I} & c_{2II} \\ 0 & c_{3II} \end{bmatrix} \begin{bmatrix} P_I \\ P_{II} \end{bmatrix} = rhs$$

$$\begin{bmatrix} c_{1I}m_{1I}c_{1I} + c_{2I}(m_{1I}+m_{2II})c_{2I} & \boxed{c_{2I}(m_{2I}+m_{2II})c_{2II}} \\ \boxed{c_{2I}(m_{2I}+m_{2II})c_{2II}} & c_{2II}(m_{2I}+m_{2II})c_{2II} + c_{3II}m_{3II}c_{3II} \end{bmatrix} \begin{bmatrix} P_I \\ P_{II} \end{bmatrix} = rhs$$

But, element-by-element formation looses the off-diagonal terms

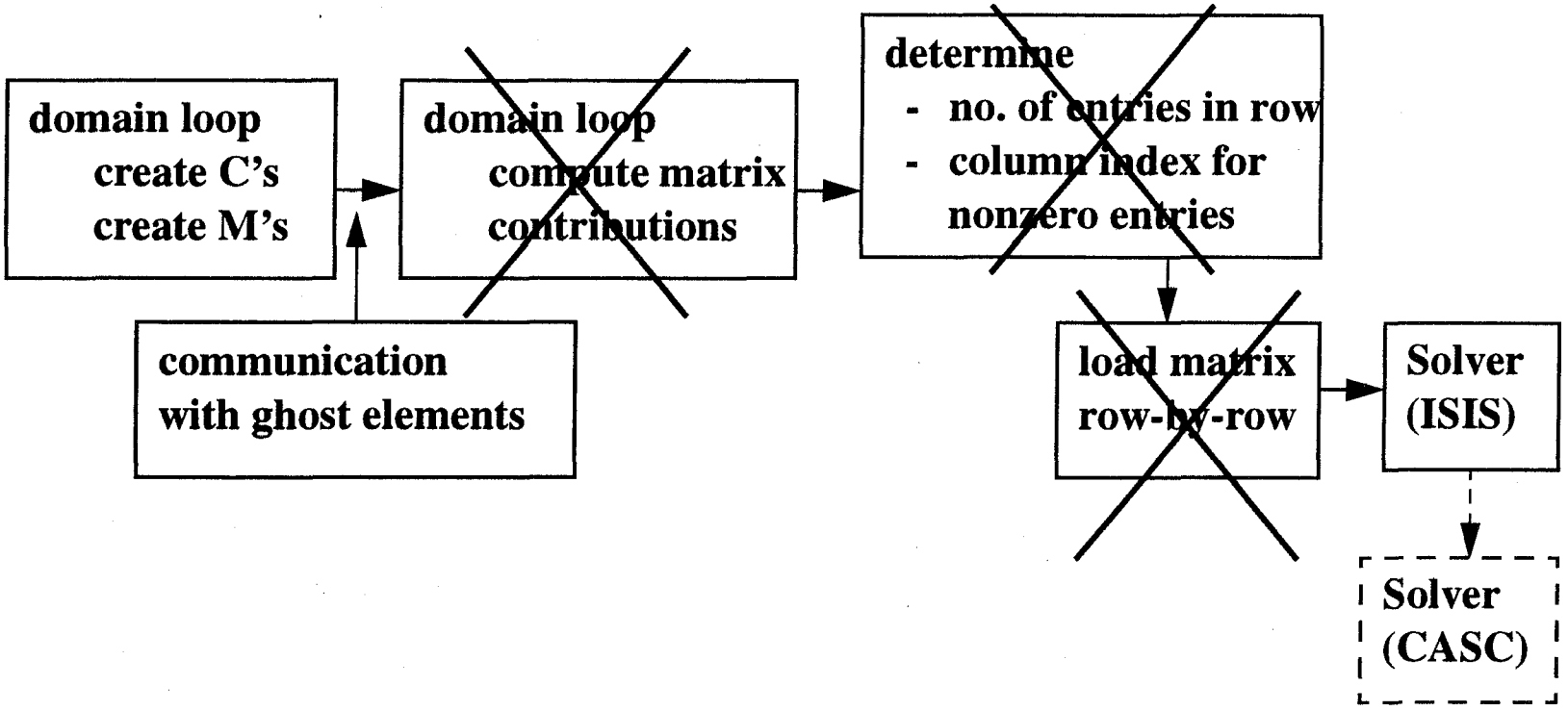
$$\begin{bmatrix} c_1 & c_2 \end{bmatrix} \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \end{bmatrix} [P] = rhs$$

$$(c_1 m_1 c_1 + c_2 m_2 c_2)P = rhs$$

The matrix multiply must be done globally.

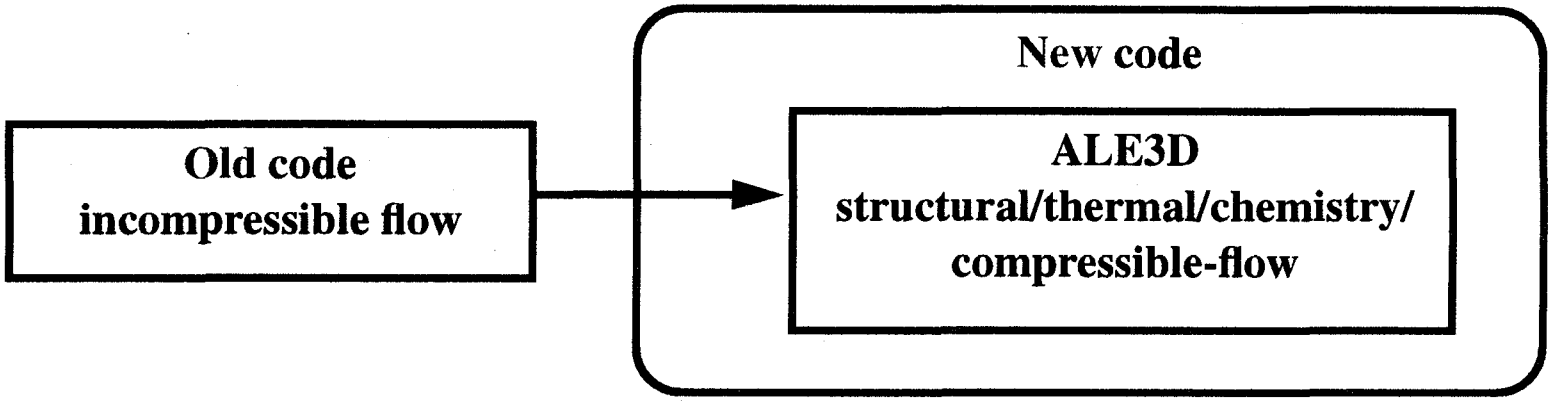
If the FEI performs the matrix multiply, the parallelization effort is significantly reduced.

Parallelization outline



A complete but expedient V&V method will be used.

Verification & Validation

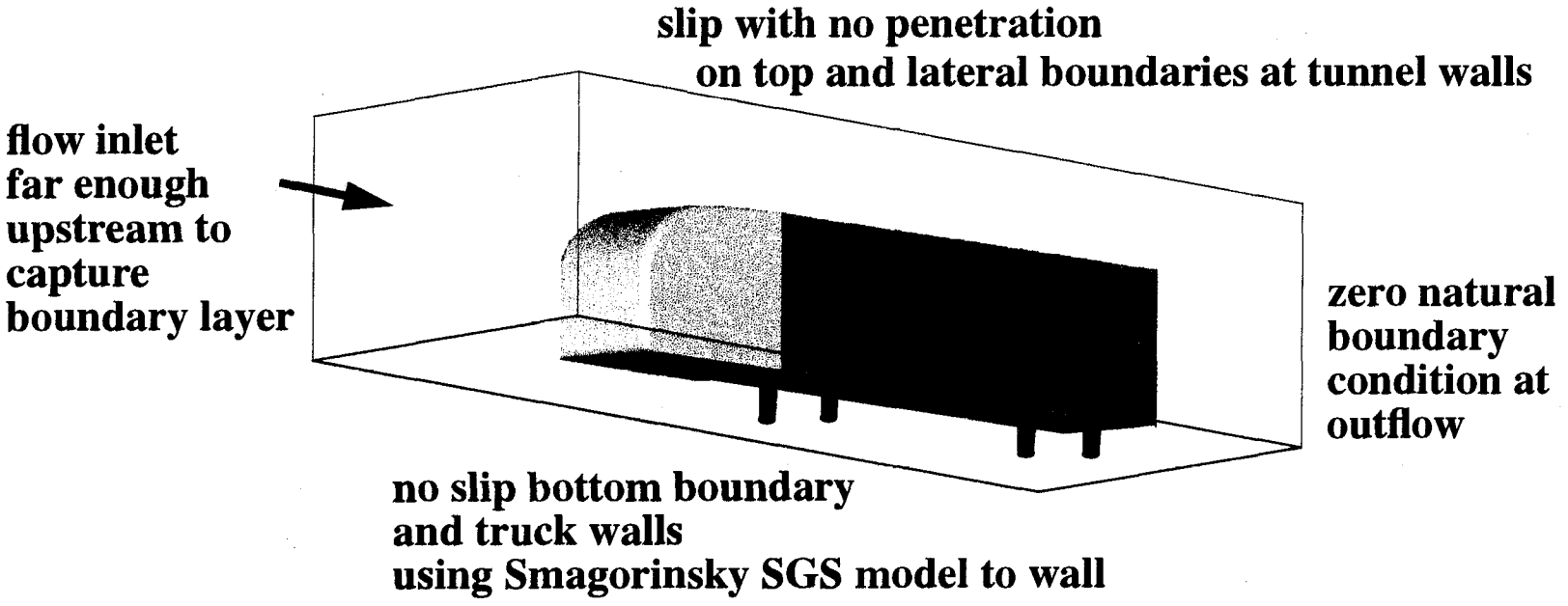


For an existing example problem (e.g., backward-facing step)

Question	Cases
Do old and new code agree?	compare to serial run with direct solver
Does iterative solve work?	compare serial run with iterative and direct solve
Does code run in parallel?	compare serial vs. parallel run for iterative solve

Simulating the NASA 7'x10' wind tunnel experiment is the demonstration problem.

Domain and boundary conditions are chosen to minimize grid size



Compressible as well as incompressible simulations can be performed with an unstructured grid.

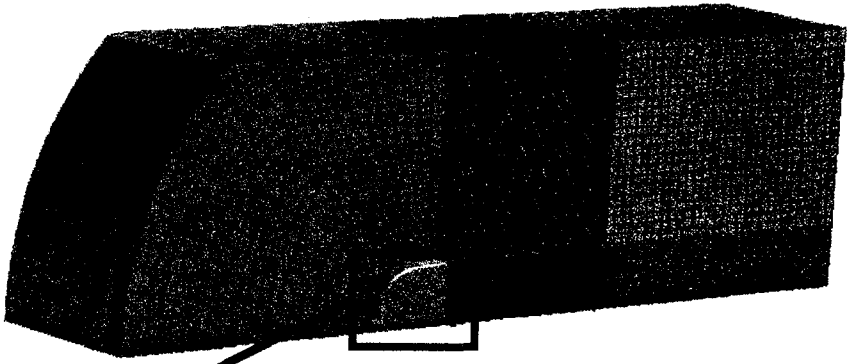
Plan

Compressible (Ma > .1)

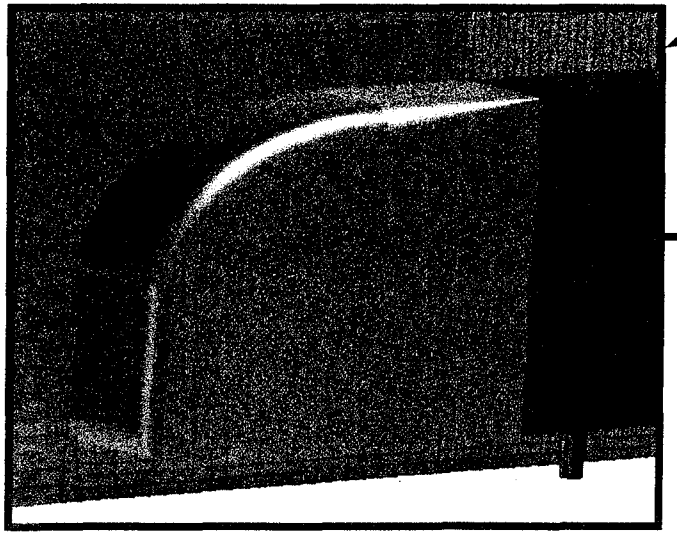
- **NASA 7'x10' results for Ma = 0.27**

Incompressible (Ma < .1)

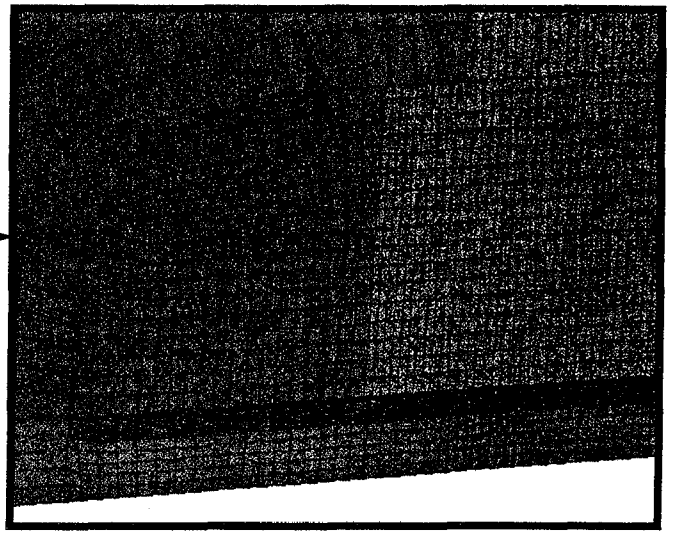
- **NASA 7'x10' results for Ma < 0.1**
- **USC results for 200,000 < Re < 400,000**
- **Texas A&M for Re = 1,600,000**



unstructured grid



removing truck



Paper Review: LES is not feasible for attached flow (wings), but desirable for separating flow.

Comments on the Feasibility of LES for Wings, and on a Hybrid RANS/LES Approach

P.R. Spalart, W-H. Jou, M. Strelets, S.R. Allmaras, 1998.

Detached-Eddy Simulation (DES) method looks promising
DES offers RANS in the boundary layers and LES after massive separation, within a single formulation.

For thin shear flows the grid resolution exceeds current capabilities (e.g., front/sides of cab)
... (for a wing) we find the need for 10^{11} grid points, under the most favorable conditions. Today, a calculation with 10^{8} points is impressive.

Coarse grids can be used in separation regions (e.g., truck wake)
... the most challenging flow regions for turbulence models "trained" in thin shear flows are the regions of massive separation ... driven by low-aspect-ratio features such as wheels and flap edges. This is where LES is most desirable ... would not require orders of magnitude in grid refinement.

Unstructured and adapted grids are required
... the grid coarsens as soon as possible outside the boundary layer; the irrotational region allows a grid spacing much larger than the boundary-layer eddies.

Much has been done and much needs to be done.

LES/FEM has advantages

- Accuracy with less empiricism
- Built-in outflow conditions and unstructured grids

LES/FEM has challenges

- Wall approximations
- Parallel computations
- Data analysis methods

Approach

- Take advantage of existing methods and codes - keep it simple

Current Technology

- DES method attempts to solve boundary layer resolution problem

LES/FEM is a challenge but we have the experience and resources to succeed.

Vortex Methods for Flow Simulation

California Institute of Technology

Essentials

- Numerical technique to solve the Navier-Stokes Equations
- Suitable for Direct Simulation and Large-Eddy Simulation
- Uses vorticity (curl of the velocity) as a variable
- Computational elements move with the fluid velocity

Advantages

- Computational elements only where vorticity is non-zero
- No grid in the flow field
- Only 2D grid on vehicle surface
- Boundary conditions in the far field automatically satisfied

Vortex Method as a Flow Model

Previous limitations (1960s and 70s)

- Inviscid model – dynamics of the boundary layer ignored
- Computationally limited – $O(N^2)$ operations per time step
- $N =$ only a few hundred to a few thousand computational elements feasible
- Dynamics of the wake and force coefficients dependent on adjustable parameters

Recent Developments (90s)

- Viscous effects treated accurately
- Fast Vortex Algorithm – $O(N)$ operations per time step
- $N =$ one to 10 million computational elements feasible
- Dense system of computational elements solves fluid equations
  - Direct simulation for low Reynolds number
  - Large-Eddy simulation for high Reynolds number
- Large-scale parallel computing

Treatment of Surface Vorticity

Standard Panel Method for N Panels

- Low order accuracy – first order accurate
- Computationally and storage limited – $O(N^2)$ matrix elements computed and stored with $O(N^2)$ operations per time step
- Only $N =$ to feasible

Advanced Panel Method

- High accuracy – third order accurate
- Computationally efficient – $O(N)$ storage locations with $O(N^{/2})$ operations per time step [can go to $O(N \quad N)$ or $O(N)$]
- $N =$ to no problem
- Triangular mesh with automatic refinement

Large-Eddy Simulation

Direct Simulation not Sufficient (1990s)

- Direct Simulation possible for Reynolds No.= to
  (at parking speeds – 0.01 mph)

- $N =$ elements (approx 400,000 GBytes) required for Reynolds No.=
  (at highway speeds – 70 mph)

Large-Eddy Simulation Required

- Treatment of small-scale (subgrid-scale) turbulence in the wake

- Treatment of small-scale turbulence in the boundary layers

- Treatment of fluidic actuators, blowing/suction, vortex generators and other flow control devices

Status / Future Work

- Fast adaptive panel method
- Panel method interaction with outer flow via method similar to Verzicco
- Subgrid stress model for Large-Eddy Simulation
- Implementation of the Vortex Method for complex geometries