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

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*U.S. Department of Energy*

Lawrence Livermore National Laboratory

# July 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 University of Southern California, Los Angeles, California on July 30, 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 University of Southern California's (USC) experimental plans and results and the computational results from Lawrence Livermore National Laboratory (LLNL) and Sandia National Laboratories (SNL) for the integrated tractor-trailer benchmark geometry called the Sandia Model. Much of the meeting discussion involved the NASA Ames 7 ft x 10 ft wind tunnel tests and the need for documentation of the results. 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), LLNL, SNL, USC, and California Institute of Technology (Caltech). This report contains the technical presentations (viewgraphs) delivered at the Meeting, briefly summarizes the comments and conclusions, and outlines the future action items.

## Summary of Major Issues

There were 3 major issues raised at the meeting.

1. Our funding is inadequate to satisfy industries request for high Reynolds number experimentation and computation. The team would prefer Reynolds number increases

in more gradual increments with careful validation and verification of computations with experiment. However, if we hope to have industry lobby Congress, we will have to provide high Re results with possibly not so careful verification and validation.

2. The NASA experiments need to be documented with
   - how and where measurements were made,
   - uncertainties in measurements,
   - corrections for comparison to Texas A&M results, and
   - wind-weighted results.

   A related issue is the inlet profile required by the computational models. SNL and LLNL will need to determine some way of approximating the 'unknown' inlet velocity profile so as to not significantly increase the required computational effort.

   Some of the experimental data (with corrections) is needed prior to the November Workshop. NASA's focus for next year should be to complete documentation of all test results.

3. The presentations for the November Workshop should be carefully planned with consideration of industry's interest, a display of our computational capabilities, and discussion of our gained understanding of important truck flow characteristics. Follow-up discussions or a meeting is needed to decide on the final agenda for the Workshop and decisions need to be made soon.

## 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 commitments can be made to a location and date. The Workshop will be scheduled in conjunction with the SAE Truck and Bus Conference, Detroit, Michigan in November 1999.

Jules Routbort of DOE OHVT and Argonne National Laboratory provided an overview of the OHVT budget for fiscal year (FY) 2000. The Aero Team's estimated costs for FY 2000 is $1.2 Million which would require almost 60% of OHVT's total budget, which is not a reasonable expectation. Jules emphasized the importance of industries positive support for this project.

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

Much of the meeting discussion involved the NASA Ames 7 ft x 10 ft wind tunnel tests and the need for documentation of the results. The purpose of the tests are for validation of the computational fluid dynamics (CFD) models and for further insight into truck flow phenomena. Extensive documentation is needed to be able to perform careful code verification and validation. Also noted were the discrepancies between results obtained in the Texas A&M wind tunnel and the NASA results. Resolution of these discrepancies is needed.

It was proposed that next years NASA budget include funding for data reduction, analysis, and documentation. However, specific data and discrepancy resolution is needed before the November Workshop so that the data can be presented and comparison to computations can be made.

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

- Uncertainty analysis of all the data is needed. The basis for all uncertainty estimates should be part of the documentation.
- Base-pressure contours and their integrals with velocity at a position beyond the boattails are needed for cases with and without the boattail plates.
- To look at the variation of $C_p$ over the surface of the truck, the center-line pressure taps versus the back pressure is needed.
- The vorticity movie should display the vorticity magnitude (square root of sum of squares for each component).
- Several of the NASA wind tunnel measurements do not agree with those performed at Texas A&M on the same model, similar wind tunnel (7x10 ft test sections), but at a slightly higher Reynolds number (Texas A&M at Re = 1.6 million, NASA at 2 million). Data corrections need to be investigated and the data corrected so that differences are resolved. In particular, the freestream pressures are different. It is suspected that the pressure measurements in the NASA tunnel may have been made too close to the vehicle. Another example is the freestream velocity. It is unsure where the Texas A&M measurements were made. It is possible that the measurements were made behind the truck or derived from the pressure change measurements. It is critical that we know where and how all measurements were made for both tests.
- The inlet profile is measured at the test section entrance for an empty tunnel. Since the front of the model is less than 6 inches from the start of the test section, the inlet profile for the CFD simulations is unknown. It is critical that all future testing include inlet velocity-profile measurements that can be directly used in the CFD model.
- The time constant for the pressure-sensitive paint measurements is needed.
- The oil-film interferometry needs to be converted to contours of skin friction for quantitative comparison.

## Plans for 12' Wind Tunnel Tests

Plans for FY 2000 were to use the NASA 12-ft wind tunnel 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. Jim Ross of NASA Ames has informed the team that the 12-ft wind tunnel will most likely not be available next year because of NASA budget cuts and reduced testing.

Jim would like us to consider doing more work in the 7-ft x 10-ft wind tunnel. Some team members have suggested that NASA investigate other wind tunnels besides the NASA 12-ft tunnel. NASA could still lead this effort even if the testing is at another facility.

The consensus was that first priority should be given to the full data evaluation of the 7 ft x 10 ft tests already performed with corrections and uncertainties documented.

## USC's Wind Tunnel Tests

Fred Browand of USC made some preliminary comments on recent newspaper articles. One article showed that the number of fatalities in car-truck accidents has not changed in the past 20 years, while the number of fatalities in accidents between two cars has declined by more than two-fifths over the same period. Another article announced that Transportation Secretary Rodney Slater, pledged that the department would reduce the death toll for truck accidents with a program of 'stronger enforcement and technological innovation'. Fred also provided an article from a German publication that discussed a new Electronic Tractor Hitch from Daimler-Crysler that allows platooning of trucks. It was interesting to find that Daimler-Crysler's experiments show that the forward truck saves more fuel than the trailing truck for separations less than 8 meters. Similarly, USC has found that platooned minivans show reduction in fuel use by the lead van.

Also discussed was lack of information from manufacturers as to the possible drag reduction for Class 8 tractor-trailers. Presented was an approach which might lead to some approximations to the minimum drag that can be achieved for a truck configuration. Dividing up the drag into forebody, base, and friction drag with some increment for wheels and undercarriage, the possible drag reduction for say the Sandia body could be determined from an investigation of various trailer lengths. This could be done by computations and experiment.

Glen Landreth of USC presented the results of recent studies involving the leading-edge rounding of the Sandia Model. Several front shapes were tried in an attempt to avoid front-edge flow separation. The final new shape, with a 2 inch radius edge, achieved attached flow for Re above 130,000. Flow trips with a sandpaper roughened surface reduced this critical Re to 60,000. Varied gap distances with the new geometry were also investigated. Experimental results indicate that variation in gap distance results in large changes to the trailer drag and relatively small changes in the cab drag. The cab drag is always less than the trailer drag and the cab alone has higher drag than when paired with a trailer. The results appear to be Re insensitive for the range considered. The viewgraph presentation is enclosed.

Experimental results for tractor-trailer gap flow with a 1/14 scale model of the Sandia Body were presented by Mustapha Hammache. Videos of the motion of tufts on the trailer front and cab base were presented. Without the trailer, the flow is always forward on the top of the cab, but with the trailer, vertical and backflow is sometimes indicated. Particle image velocimetry measurements provide instantaneous results at 10 frames per second for flows at 20 m/s. This frequency is not adequate to provide real-time flow resolution, but it does provide accurate instantaneous flow snapshots and accurate time-averaged flow statistics for mean and fluctuating quantities.

A tour of the wind tunnel facility and the shop used for model construction was lead by Mark Michaelian. The floor posts on the models for force measurements are in a different location than that used for the NASA and Texas A&M tunnel experiments because of the wind tunnel floor and instrumentation setup.

Some issues discussed for future experiments are listed below.

- Surface pressures and PIV in the tractor-trailer gap is needed for determining cab base drag.
- The posts and cables should have a cylindrical shroud for ease of computational modeling.
- Model vibration should be minimized with more support.
- It is critical that all future testing include inlet velocity-profile measurements that can be directly used in the CFD model.

## 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. Some comparisons with NASA's measured friction coefficient were also presented. The one-equation Spalart-Allmaras turbulence model used in the calculations was not set to capture the transition on the front of the cab so some discrepancies between the calculated and measured friction coefficient are present on the cab front. However, the model did remarkably well at predicting the friction coefficient along the top of the Sandia Body. The viewgraph presentation is enclosed.

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 for both their incompressible and compressible flow models. The approach and development challenges were presented along with a progress update. Implementation of a subgrid-scale model for LES into the compressible model was completed. For the incompressible model, LLNL had planned to use an established pressure Poisson solution approach. However, it was found that the finite element solver interface (FEI) developed by SNL can not currently support this formulation (i.e., a global matrix that represents the Laplace operator can not be formed element-by-element as required by the interface). Reformulation of the incompressible model from the solution of a pressure Poisson equation to the direct solution of the primitive variables has been completed and some coding, debugging, and validation remain.

Dan Flowers of LLNL presented preliminary results using the compressible model that demonstrate the benefits of the unstructured grid option. A mesh of 900,000 elements was used on the LLNL IBM parallel machine, running with 128 processors. Because of difficulties in matching the curvature on the bottom-front edge of the Sandia Body, a sharp corner was used for these preliminary calculations. Several movies of the flow field were shown, indicating the three-dimensional time-dependence of the flow. It was found that in several locations (e.g., around the bottom posts and cab edges) the flow can reach relatively high Mach numbers around 0.4 to 0.5, resulting in locally significant compressibility effects.

Tony Leonard of Caltech introduced a new SGS model that promises better performance than the dynamic Smagorinsky SGS model. Tony plans to implement the model into the vortex method approach being utilized by the Caltech team. Tony also reviewed some recent European research relevant to Aero Drag. Of particular interest was the experimental work of Hans Fernholtz of the Technical University of Berlin who showed prevention of stall on high-angle-of-attack airfoils by oscillatory blowing and suction (no net mass flow) through a slot near the leading edge. Apparently a Helmholtz resonator was enough to provide the required excitation. A train of vortices was produced that moved along the airfoil and prevented separation. Mark Brady continued the presentation with an update of the Caltech team's progress in generation of surface grids for complex geometries.

Dieter Schwamborn of the German Aerospace Center in Gottingen, Germany is a visiting scientist at USC and provided us with some of his recent results using the detached eddy simulation (DES) method. DES uses a Spalart-Allmaras RANS model near walls and an LES eddy viscosity model away from walls. Dieter's model is a general Navier-Stokes solver with overset and adapting grids.

**The Truck Aero Drag Workshop III in November and Future Meetings**

It was emphasized that the industrial participants at the Workshop will be interested in higher Reynolds number experiments and computations than can be currently provided. The team also expressed their concern that future funding is not adequate to address the high Reynolds number effects any time soon. However, to acquire more funding, we need the truck industry to be our advocates and lobby Congress.

It was decided that a considerable effort should be put into careful planning of the Workshop presentations and that our computational effort and data evaluation before the Workshop should focus on key results of most interest to industry. Several team members will try to visit NASA soon and work with them in determining the data evaluations and analyses that are needed prior to the Workshop. Computations at SNL, LLNL, and Caltech will focus on modeling of the base flow with and without the boattail plates at low to high Reynolds number. USC will most likely focus their presentation on their experiments on tractor-trailer gap, providing insight into the flow phenomena and results that show the different effects on cab and trailer drag.

The next Working Group Meeting is planned the day after the Workshop to discuss the results of the workshop and to prioritize our efforts for FY2000 based in part on the results of the Workshop.

## Action Items

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

Continued data evaluation, analysis, and documentation. (Jim Ross and the NASA Ames experimental team)

Setup (small group) meeting at NASA to determine data needed prior to workshop and gain further insight into industry's interest. (D. Flowers)

Continue discussions (by e-mail, conference calls, and possible meeting) on Workshop presentations and focus efforts. (R. McCallen)

Continued workshop planning. (H. Magann)

Organize posters for booth at conference. (R. McCallen and H. Magann)

Presentation at ORNL Meeting in Tennessee. (R. Couch)

Presentation at Truck Maintenance Meeting, Tampa, Florida in October. (F. Tokarz)

Presentation at ANL Thermal Management Meeting. (R. McCallen)

# Truck Aero Team Meeting

## USC, Los Angeles, CA

## July 30, 1999

## Attendee List

| Attendee | Organization | e-mail address and phone |
|---|---|---|
| Lorena Barba | Caltech | labarba@caltech.edu, 626-395-4757 |
| Ron Blackwelder | USC | ron@spock.usc.edu, 213-740-5367 |
| Mark Brady | Caltech | mbrady@caltech.edu, 626-395-3285 |
| Fred Browand | USC | browand@spock.usc.edu, 213-740-5359 |
| Tim Dunn | LLNL | tdunn@llnl.gov, 925-422-8258 |
| Dan Flowers | LLNL | flowers4@llnl.gov, 925-422-0529 |
| Mustapha Hammache | USC | hammache@spock.usc.edu, 213-740-5377 |
| Dick Kaplan | USC | kaplan@usc.edu, 213-740-0244 or 523-691-6593 |
| Glen Landreth | USC | landreth@usc.edu, 213-387-8279 |
| David Lazzara | USC | lazzara@usc.edu |
| Tony Leonard | Caltech | tony@galcit.caltech.edu, 626-395-4465 |
| Peter Lissaman | USC | lissaman@spock.usc.edu, 213-740-5370 |
| Rose McCallen | LLNL | mccallen1@llnl.gov, 925-423-0958 |
| Eckart Meiburg | USC | eckart@spock.usc.edu, 213-740-5376 |
| Mark Michaelian | USC | michaeli@spock.usc.edu, 213-740-1078 |
| Mike Rubel | Caltech | mrubel@caltech.edu, 626-395-4475 |
| Jules Routbort | ANL/DOE | routbort@anl.gov, 630-252-5065 or 202-586-1477 |
| Walt Rutledge | SNL | whrutle@sandia.gov, 505-844-6548 or 505-844-4523 |
| Kambiz Salari | SNL | ksalari@sandia.gov, 505-844-9836 |
| Dieter Schwamborn | DLR/USC | Dieter.Schwamborn@dlr.de |

# Agenda

## Heavy Vehicle Aerodynamic Drag: Working Group Meeting

## University of Southern California

**RRB Rapp Engineering Research Bldg, Laufer Library**

## Friday, July 30, 1999

**Purpose of Meeting**

- Overview discussion of upcoming events
- DOE perspective
- Discussion of technical details of experimental and computational work in progress

| | |
|---|---|
| **Introduction** | Rose McCallen |
| **Update: NASA Test Results** | R. McCallen and K. Salari for Jim Ross |
| **Wind Tunnel Tests at USC** | |
| **Preliminary Comments** | Fred Browand |
| **Drag vs Leading Edge Rounding** | Glen Landreth |
| **DPIV Studies** | Mustapha Hammache |
| **Tour Laboratory** | Mustapha Hammache<br>Mark Michaelian<br>Glen Landreth<br>David Lazzara |
| **Doe Perspective** | Jules Routbort |
| **RANS/LES Modeling at SNL** | Kambiz Salari<br>Walt Rutledge |
| **LES Modeling at LLNL** | |
| **Compressible/Incompressible Models** | Rose McCallen |
| **Compressible Simulations** | Dan Flowers<br>Tim Dunn |
| **Vortex Element Methods at Caltech** | Tony Leonard<br>Mark Brady |
| **Spalart-Allmaras DES on Unstructured Grids at USC/Gottingen** | Dieter Schwamborn |
| **Wrap-up** | Rose McCallen |

# Aerodynamic Design of Heavy Vehicles

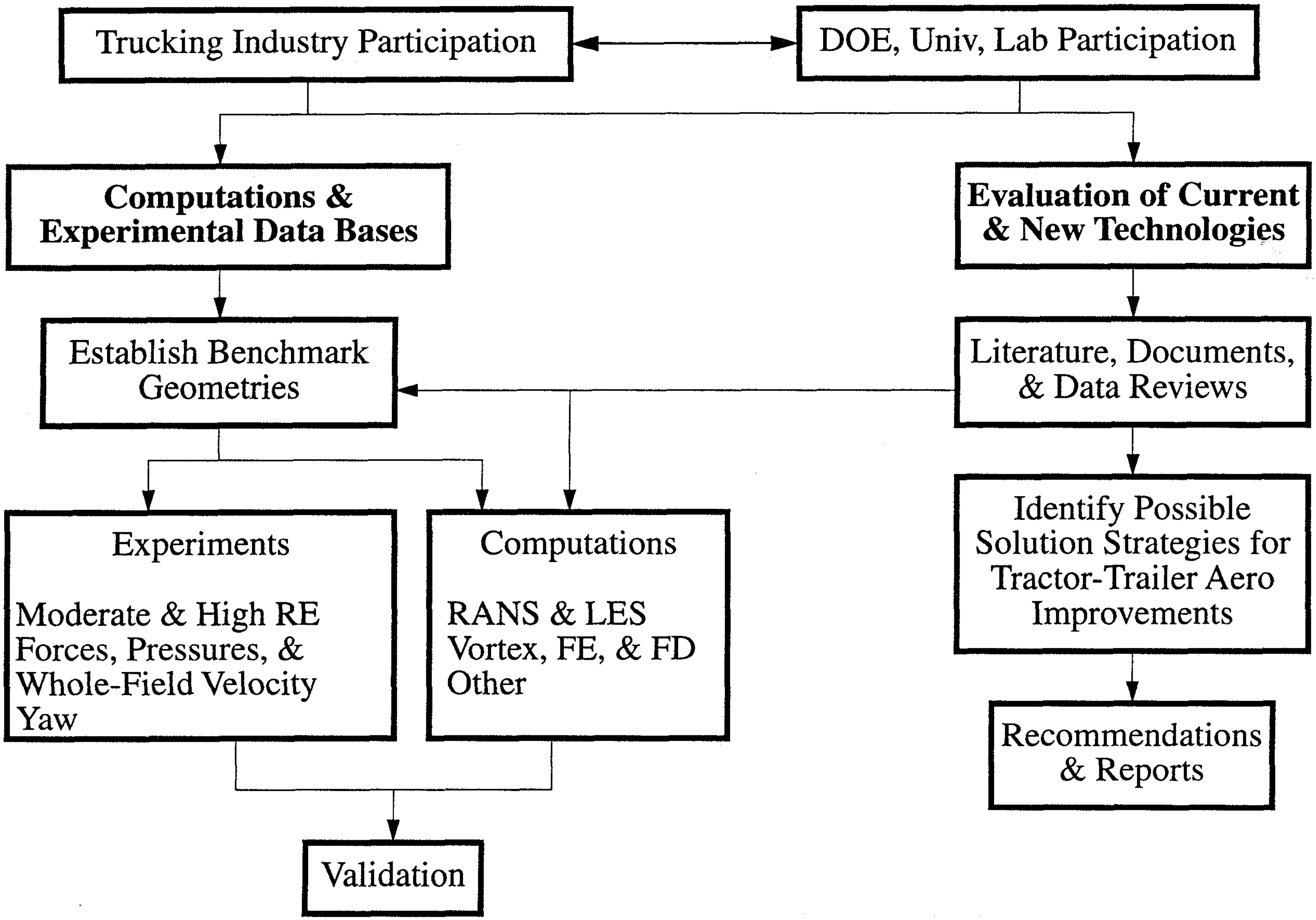
## Overview of Project

**Rose McCallen**

**Lawrence Livermore National Laboratory, Livermore, CA**

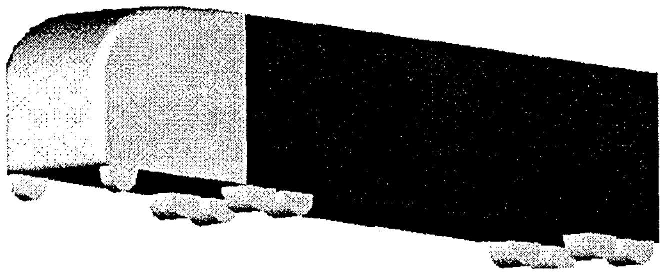
**July 1999**

## The project focus is on development and demonstration of a simulation capability.

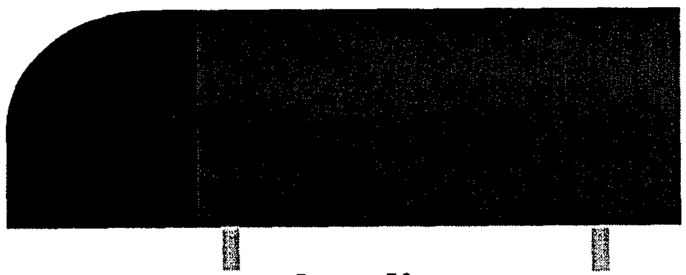


# Near-Term: Comparison of RANS and LES and detailed experimental verification for a truck problem.

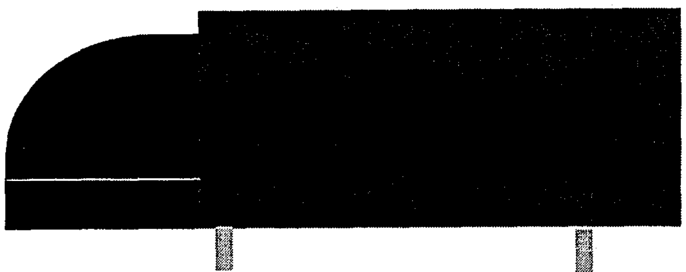
**Sandia's Model**



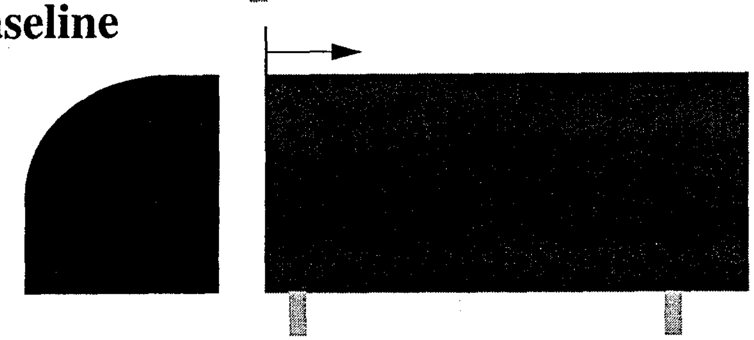

**Simple geometry with some existing data and some modeling already done**



baseline



height mismatch



gap

# Our near-term tasks have been identified and prioritized.

Benchmarks

1. Sandia Body

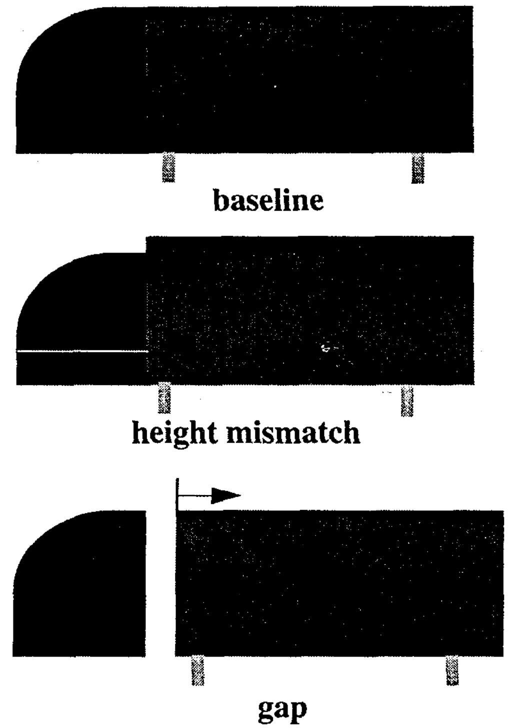
   Experiments

   - 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 - in progress

   Computations

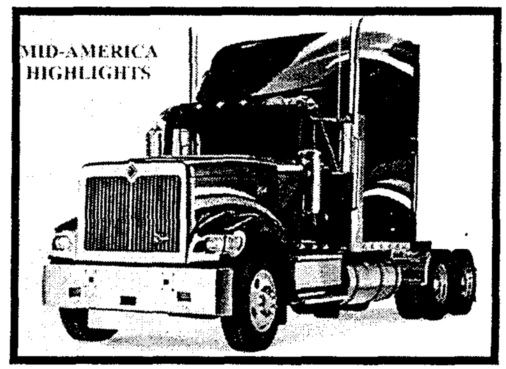
   - RANS for high and low Re (SNL) - in progress
   - LES for low Re, attempt at high Re (LLNL and Caltech) - in progress




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



# 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, 7/99 |
| 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 |

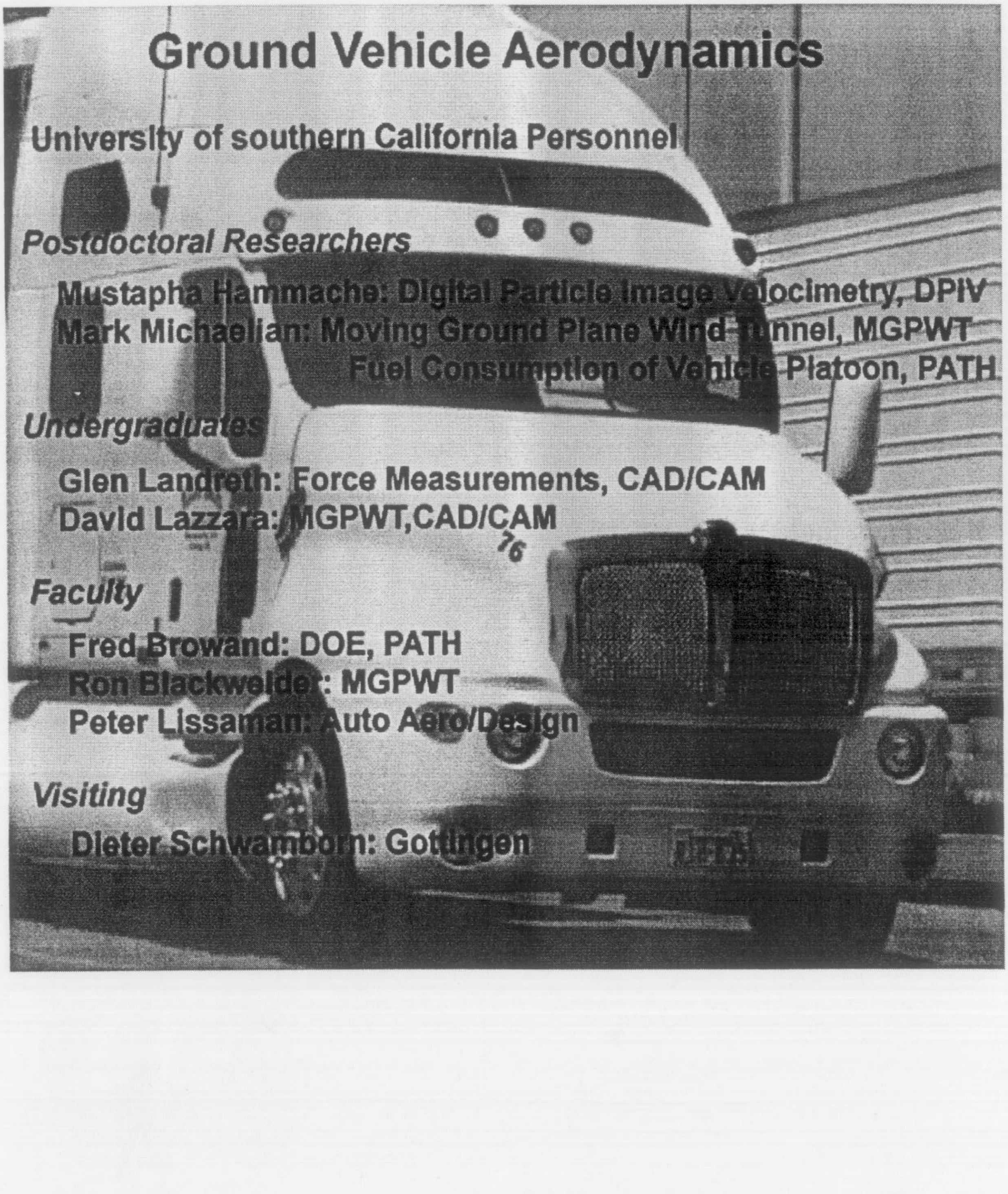
# Our budget is not consistent with projected funding.

| | Computations & Experiments | Evaluation of Current & New Technologies | Final Report | Total requested/ Year | Total received/ Year |
|---|---|---|---|---|---|
| **FY98** | $276K | $34K | | $310K | $325K |
| **FY99** | $630K | $5K | | **$635K** | **$441K** |
| **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 | $31K |
| | | |
| Totals | $325K | $441K |

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


Ground Vehicle Aerodynamics
University of southern California Personnel
Postdoctoral Researchers
Mustapha Hammache: Digital Particle Image Velocimetry, DPIV
Mark Michaelian: Moving Ground Plane Wind Tunnel, MGPWT
Fuel Consumption of Vehicle Platoon, PATH
Undergraduates
Glen Landreth: Force Measurements, CAD/CAM
David Lazzara: MGPWT,CAD/CAM
Faculty
Fred Browand: DOE, PATH
Ron Blackwelder: MGPWT
Peter Lissaman: Auto Aero/Design
Visiting
Dieter Schwamborn: Gottingen

# Full Speed Ahead in Heavy Traffic

*A free translation from ZEIT No. 25, 17-6-99 by Frieder Necker and Fred Browand*

Early in June 1999, Daimler-Chrysler (DC) presented an Electronic Tractor Hitch (ETH) to several journalists. With this device, two trucks are coupled by an infrared system. The driver of the second truck can rest while driving at full speed. Hartmut Marwitz, DC's chief truck designer, believes that it is possible for trucks to couple and decouple on the highway—thus building Australian-like road trains (or platoons) in which the duty of steering remains with the first truck. If different companies are involved, charges for the steering work could be determined via the Internet.

However, Hartmut still sees many obstacles in the way before this vision becomes a reality: "Right now we have to adjust the legal framework for the increased technical possibilities." In the aviation industry, fly-by-wire is already a reality, but travel over-the-road still forbids steer-by-wire. Changing the regulations is not the task of the German government: rather it is a task for the European Community in Brussels that places a premium on safety issues. Today, safety is still an uncertainty. However, engineers believe that in the future the ETH concept will provide an additional level of safety just as, for example, the implementation of the ABS braking system has provided. The reason is that electronic 'reaction time" is much faster than human reaction time. The increasing number of rear end accidents could be lowered by the utilization of such an electronic system, and the capacity of the highways could be significantly increased by employing a shorter, safe-travel distance between vehicles. It is important to note that fuel savings can be achieved for both trucks.

The program, "Promote Chauffeur" is 50% funded by the European Community and 50% funded by DC and other leading truck-manufacturers (e.g., Iveco) in concert with the long-haul truck related industry group. The program goals are "optimization of truck traffic on European highways" and the "easing of driving stress". The basic idea is to develop a brand independent system, enabling trucks of different manufacture to couple. MAN, a German truck builder, is currently developing a system termed Adaptive Cruise Control (ACC) for buses and trucks to maintain the proper safety distance while using the cruise control. This project is partly funded by the German government ($35M), and involves some 60 companies and research institutes. In operation, ACC constantly updates the distance to the forward vehicle by means of radar, and maintains a constant separation. DC will soon offer a similar system for automobiles. However, in either system, the drivers are still required to steer.

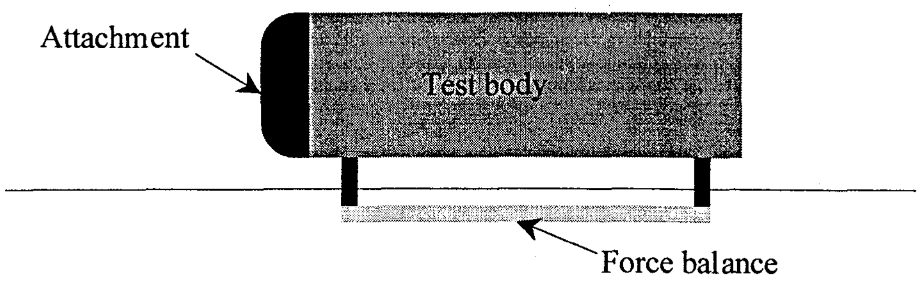
The ecological advantage of fuel savings in the range of 10-15% is noted by DC's Marwitz. Interestingly, experiments have shown that at separations below 8 meters, the *forward truck saves more fuel than the trailing truck.* With a fuel cost in Europe of approximately $35K per truck per year, a 10-15 % saving is considerable. After 18 months of operation, the ETH should reach a break-even point, and the truck owners begin to save money. In this win-win strategy, both truck owners and manufacturers of ETH benefit. Polls show that 65% of the truck owners would be interested in purchasing such a system.

Today the proposed separation distances of 6-15 meters is clearly illegal, but with a functioning electronic link, safe travel is possible according to Hans-Georg Metzler of DC. In operation, the instantaneous status of the steering, braking, and the engine operating point of the lead truck is continuously transmitted to the trailing vehicle. The separation distance is measured optically by means of an infrared emitter. The infrared emitters are placed in a circle at the rear of each truck. Two infrared-sensing cameras track the emitters, and estimate the distance between the trucks by the size of the circle. In spite of the two-camera back-up system, one must consider other safety issues. For example, what would happen if the first truck were to leave the road unexpectedly? In the current set-up, the second truck would follow. Of course, the system must be improved to avoid this kind of malfunctioning before selling it to customers. American researchers (PATH at Berkeley, CA) try to solve such problems by placing magnetic devices in the highway (as on I-15). European researchers think it infeasible to assume such additional infrastructure, and have developed a video-camera system able to detect and track street signs, road markings, obstacles, etc. This would make fully automatic trips on the highway possible. Additionally, one could use GPS for exact positioning. The European Community plans to establish a separate satellite system for this purpose.

Would truck drivers want such changes? Would the danger of unemployment increase? Karl Heinz Schmidt of the trucker union is skeptical about the ETH. In his opinion the fuel savings are less than expected. Furthermore he envisions large liability issues when coupled trucks are involved in accidents. He predicts that ETH will not be accepted for psychological reasons. The German AAA is also a lukewarm supporter; they foresee serious safety problems arising, for example, as vehicles overtake and pass a platoon of coupled trucks. DC engineers minimize the danger of increased unemployment for truck drivers; they view ETH as a tool that will make truck driving easier and less stressful. Moreover, there is no present plan for truckers to take their mandatory rest periods while in a platoon configuration.

Marwitz (DC) expects ETH to be ready for the market in 5 to 8 years. But even though a fully automatic system may be 50 years down the road, truckers will never be replaced. "In the end, this is a decision that the society must make. Remember, boiler tenders from the era of steam power existed for many years on electric locomotives."

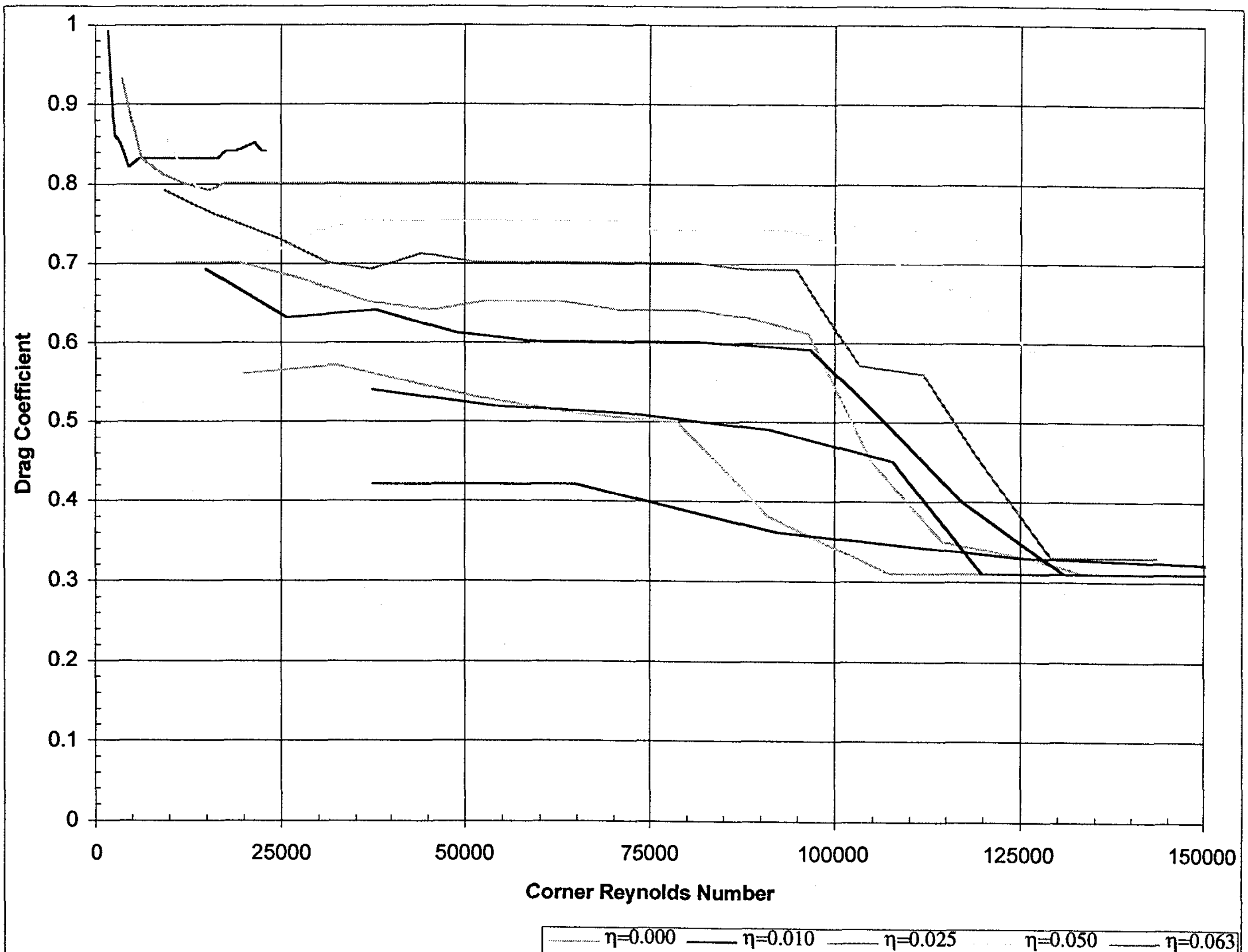
# Previous work




$$\mathrm{Re}_C = \mathrm{Re}_{\sqrt{S}}\,\eta$$

$$\eta = \frac{R}{\sqrt{S}}$$

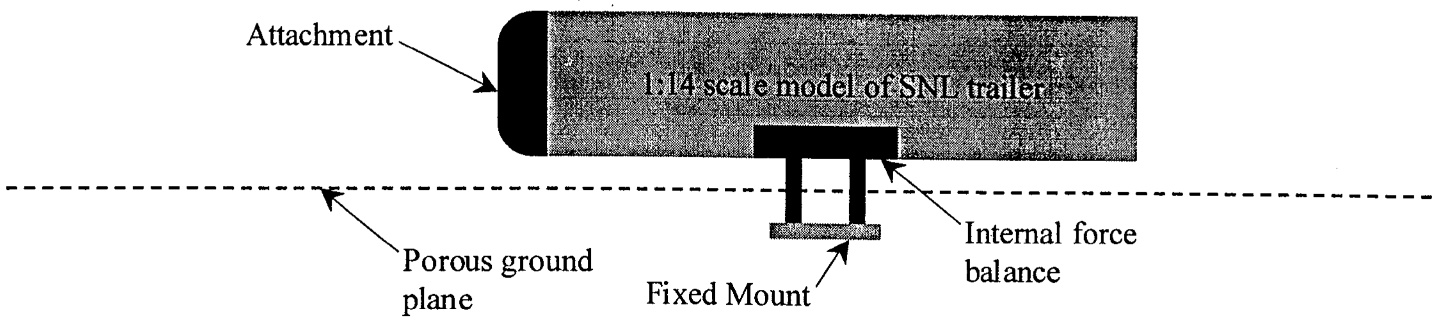
Found dramatic decreases in drag with increasing Re_C.
Change is attributed to presence or absence of leading edge separation.
Flow stays attached at Re_C=130,000.



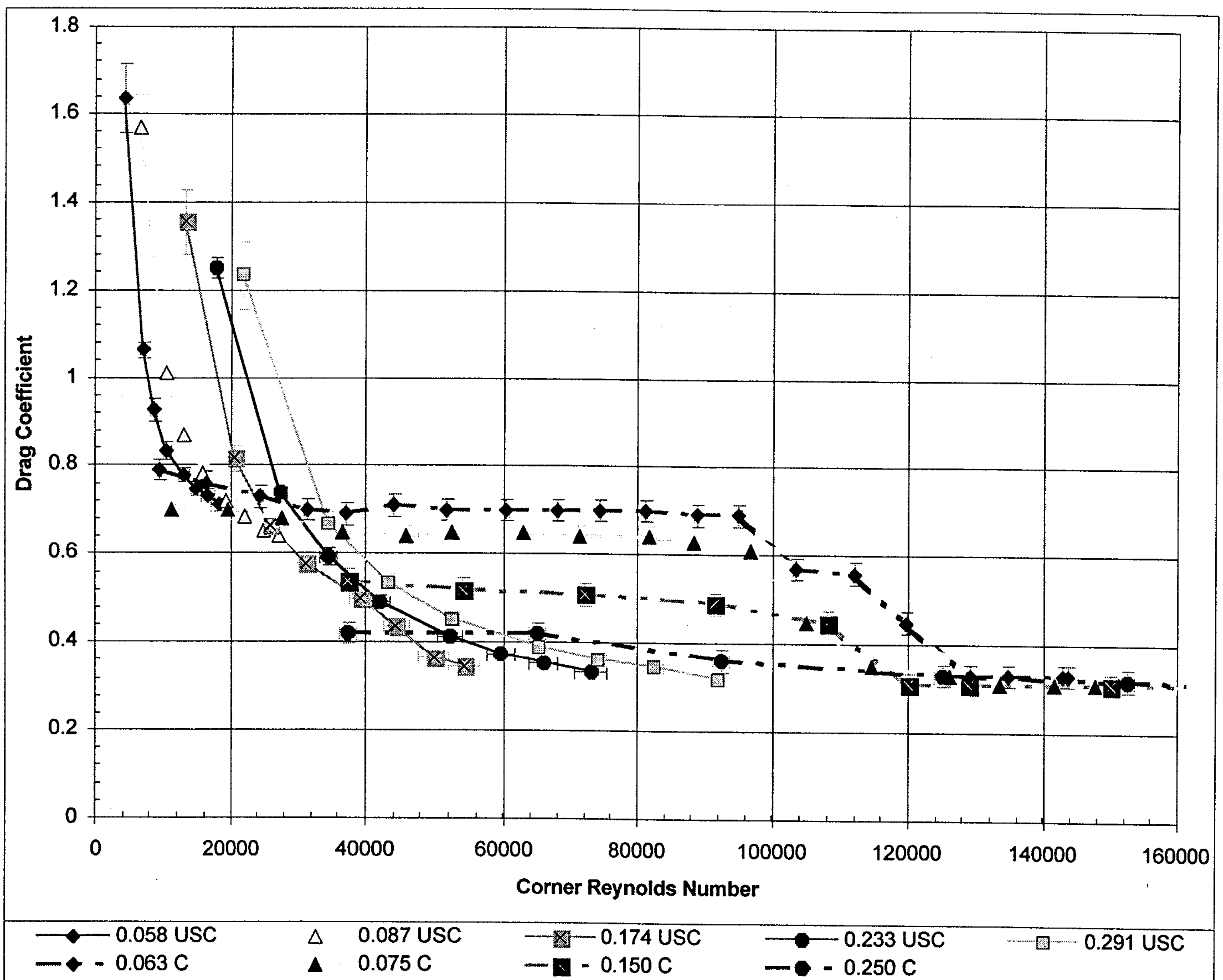

**Corner Reynolds number plot of Cooper data**

Cooper, Kevin R. *The Effect of Front-Edge Rounding and Rear-Edge Shaping on the Aerodynamic Drag of Bluff Vehicles in Ground Proximity*, SAE Paper 850288, 1985.

# USC test of trailer attachments

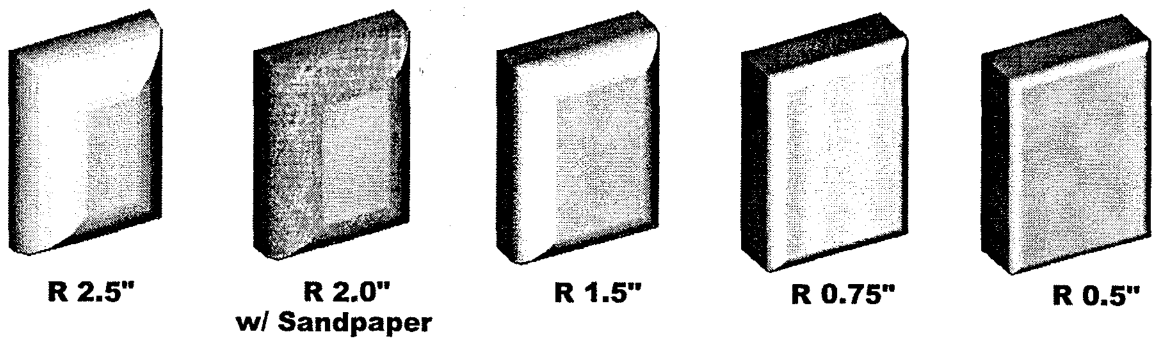



Two experiments are consistent:
- Show the same behavior.
- Reach the same asymptote with large radii.



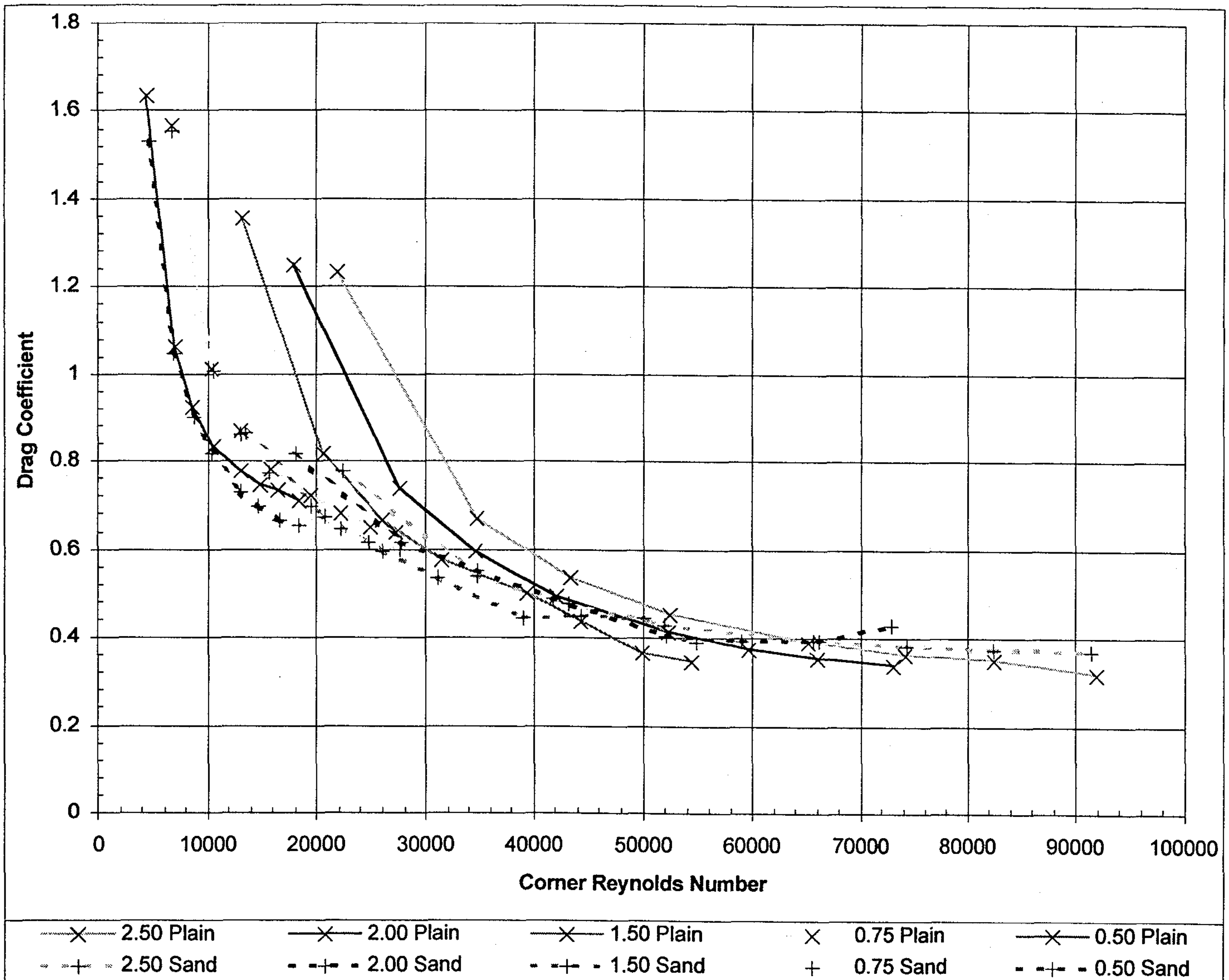

Corner Reynolds number comparison of USC data to Cooper (C) data

# Test of tripped trailer attachments



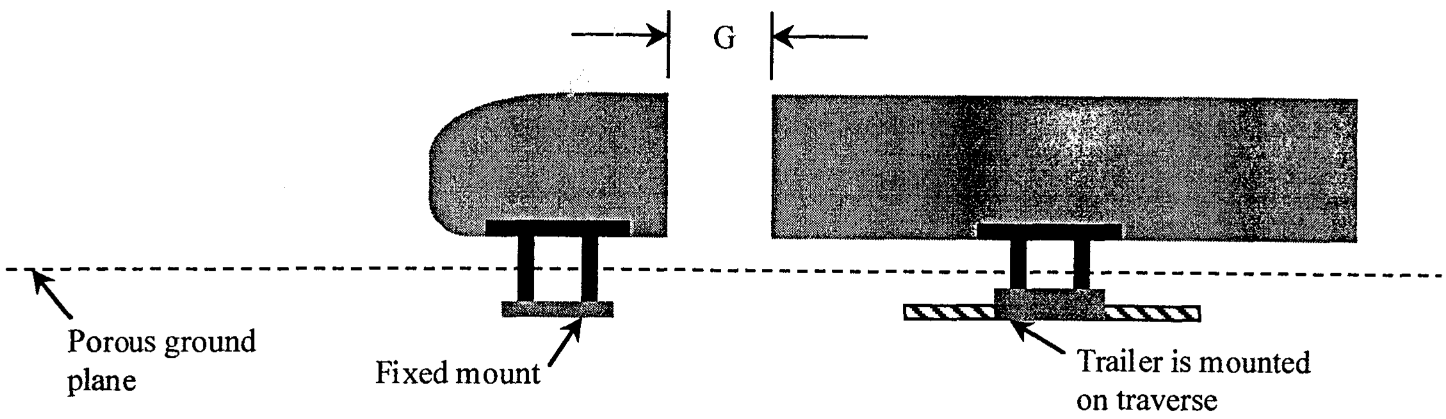

Tested several trip designs.
Sandpaper was most effective:
- •Reduced critical Re_C up to 30%.
- •Cooper reports up to a 50% drop.

Chose 2" radius for new cab model.

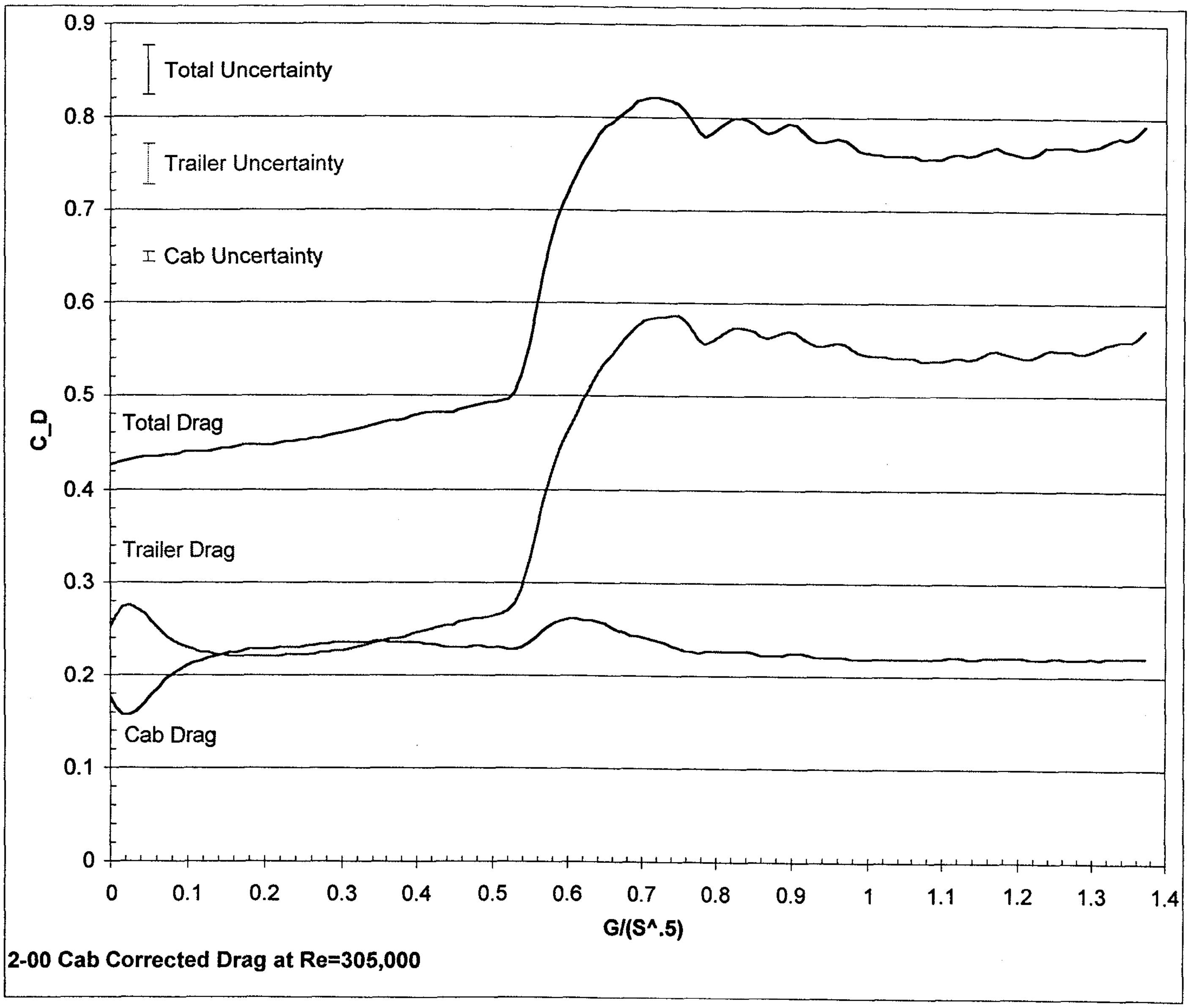



Corner Reynolds number comparison of plain & sandpapered attachments

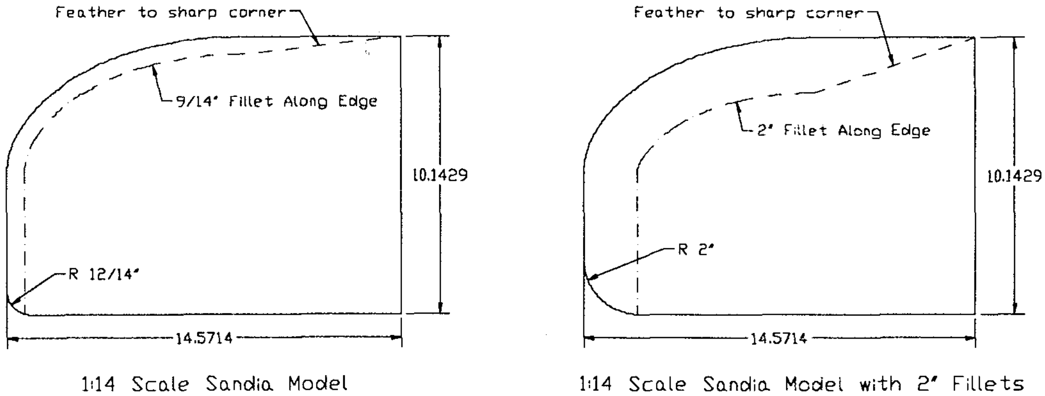
# Test of cab-trailer with varying gap



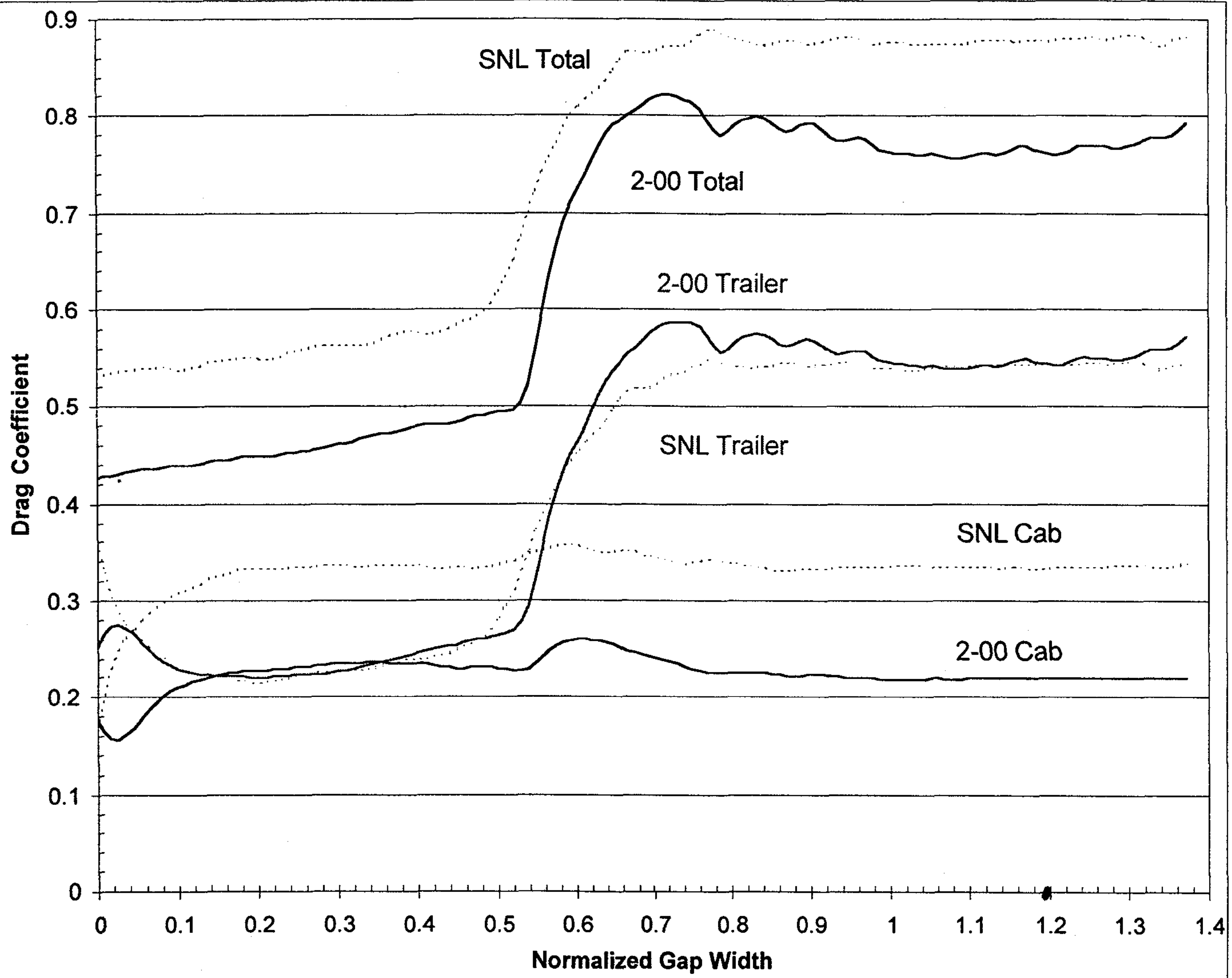

Cab drag is fairly constant, except at small spacings and small rise between 0.5 and 0.8 G/L.
Trailer drag increases rapidly, 100% increase between 0.55 and 0.75 G/L.
Total drag is dominated by trailer drag and peaks around 0.75.
Major features are independent of Reynolds number.



# Cab geometry effect upon varying gap drag

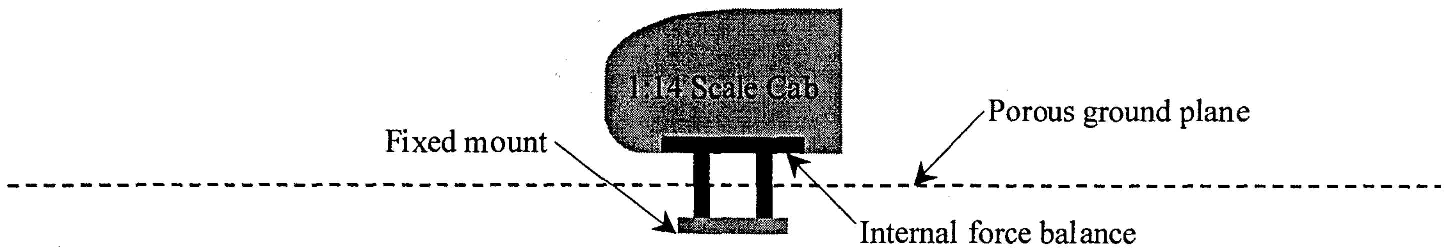



SNL Cab has consistently higher drag than 2" cab.
Trailer in SNL test has nearly the same behavior as the trailer in the 2" test.
Transition to high drag is not as rapid, due to increased "shielding" by SNL cab.

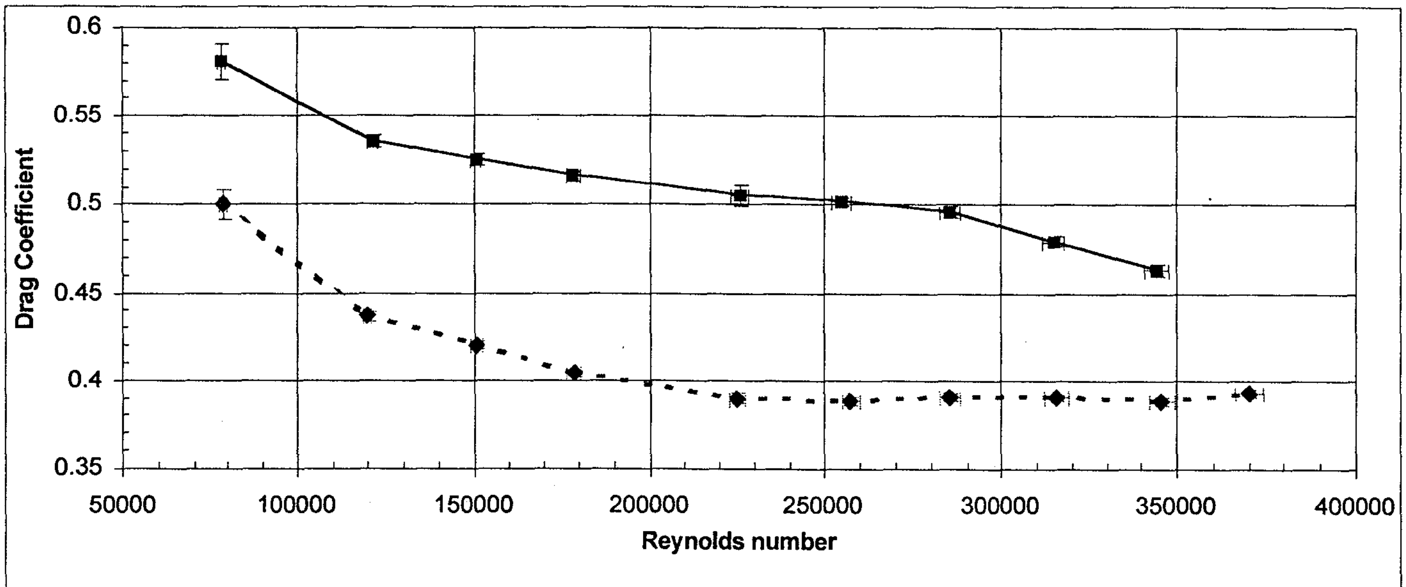



Comparison of two geometries at Re=305,000

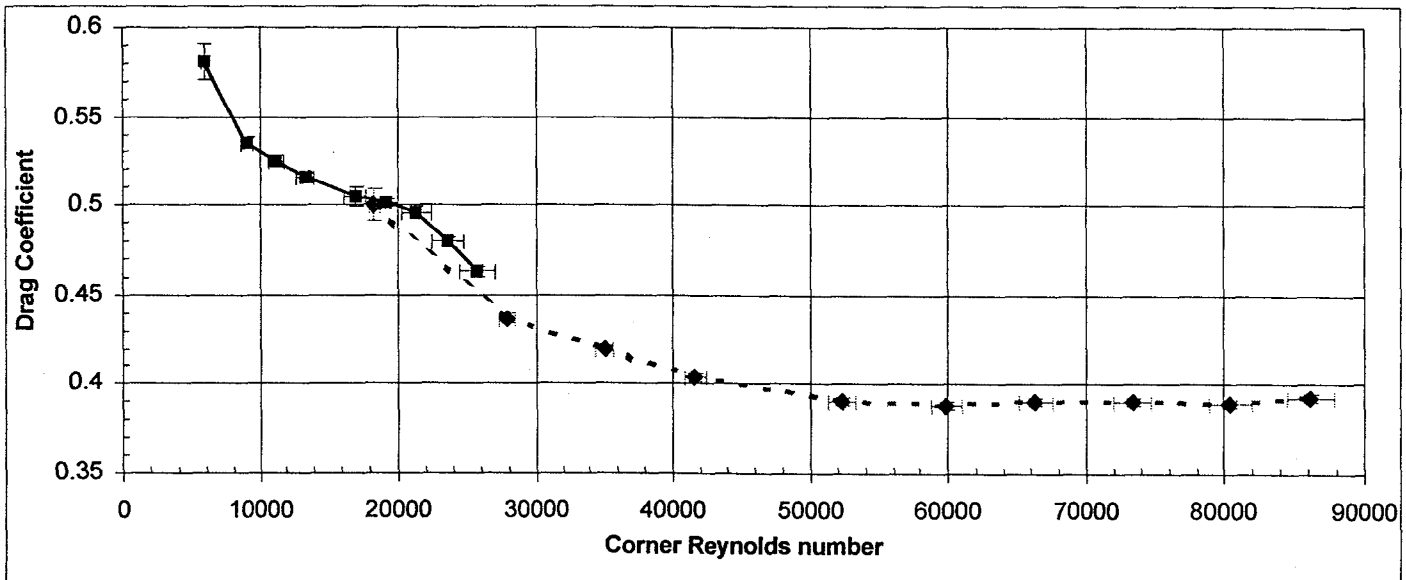
# Comparison of two cabs in isolation




Isolated drag coefficients are larger than those with measured with trailer, even at large gaps.
SNL cab has much higher drag that 2" radius cab.
Two curves are very close, indicating that Re_C is a critical variable.
Which is more important, geometric fidelity or flow similarity?

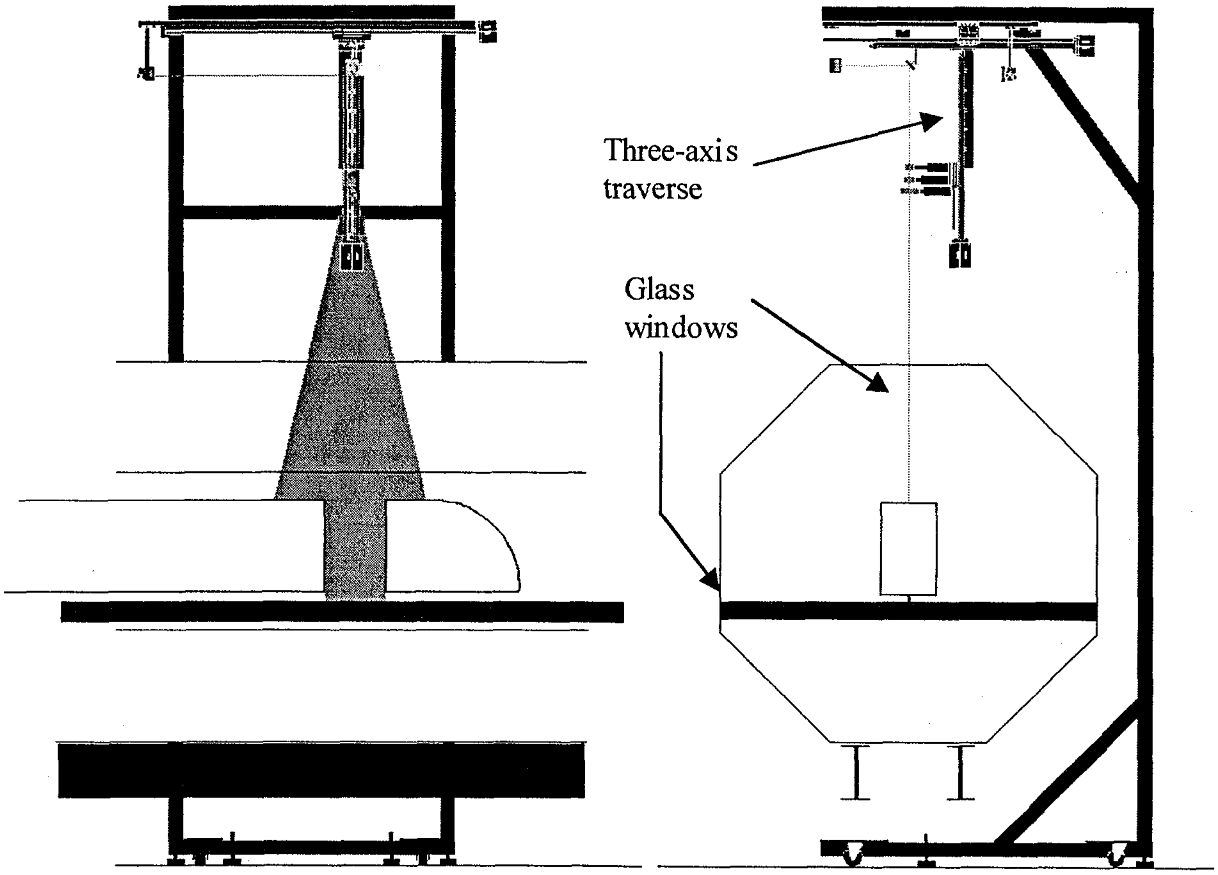



**Reynolds number comparison of isolated cabs**




**Corner Reynolds number comparison of isolated cabs**

# Experimental arrangement

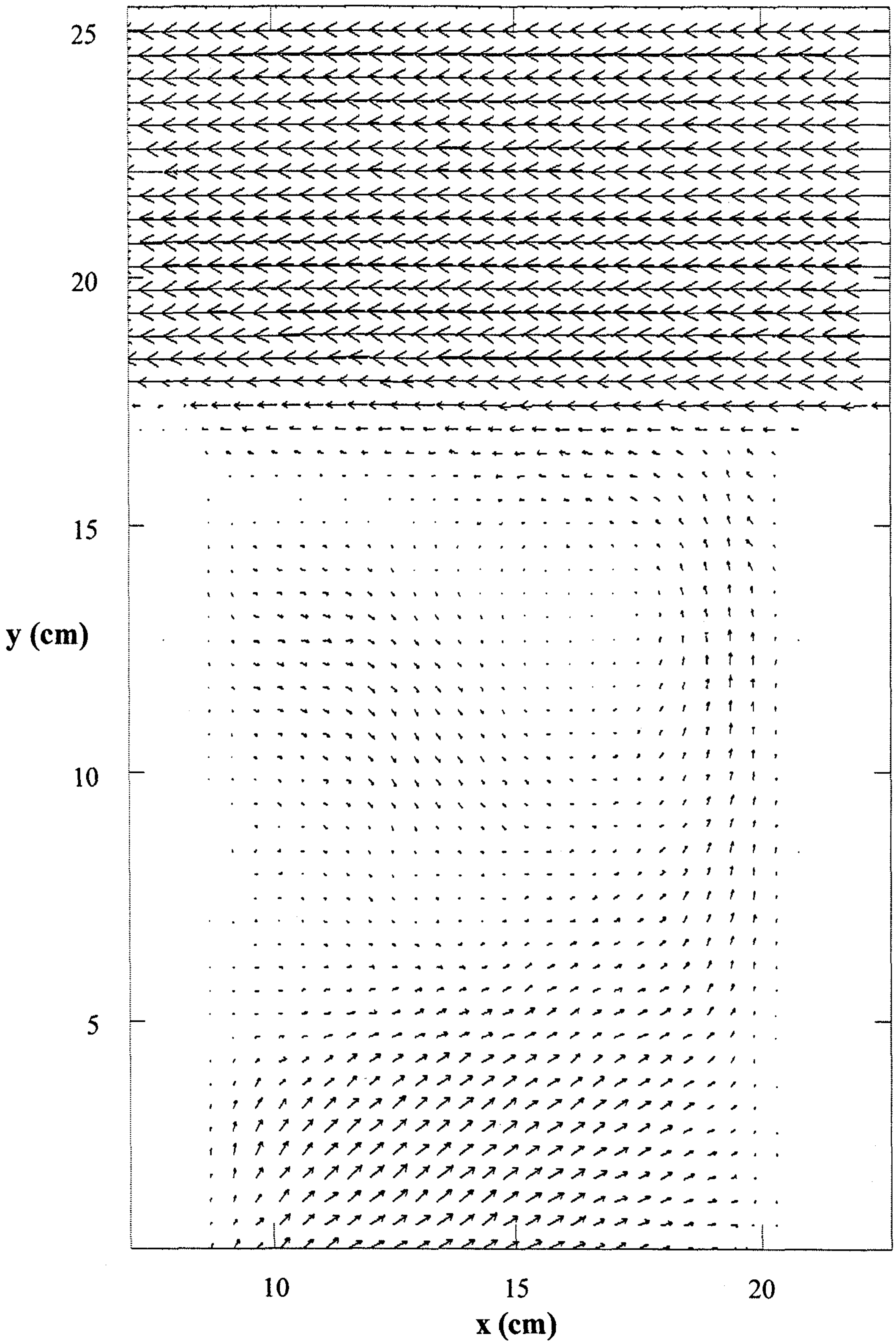



Future measurements will be made in different vertical and horizontal planes so as to cover the entire cavity in the gap. For this purpose, two independent three-axis traversing mechanisms are being constructed. The traverses are motorized and their motion is synchronized so that the laser light sheet and camera scan a cube rapidly without loss of image focus.
The sketches above illustrate the use of the system to scan a vertical light sheet (only the top traverse is shown). The camera is mounted on a similar traverse facing the side window. The camera and light sheet optics are easily swapped between traverses to acquire data in horizontal planes.

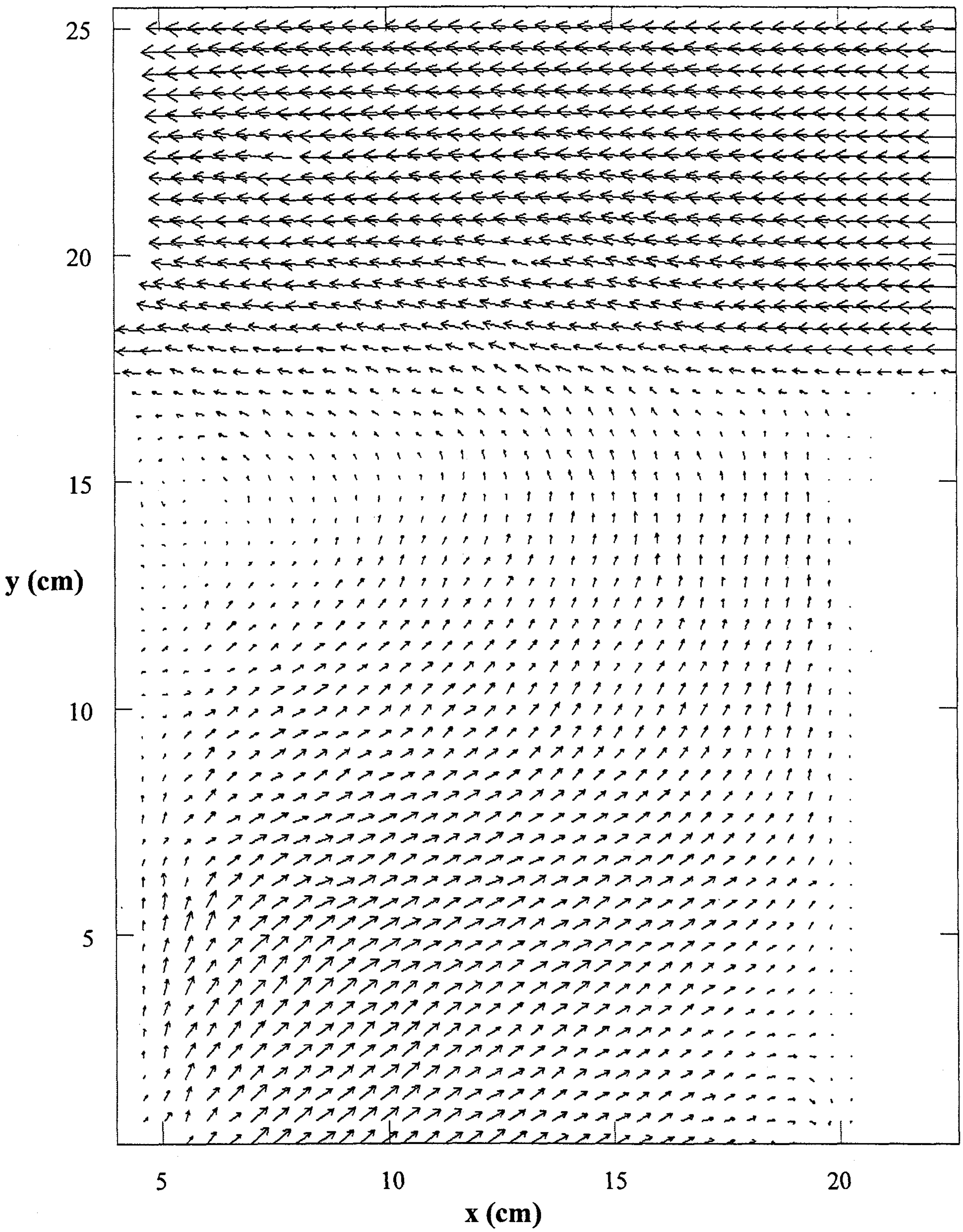
Preliminary PIV measurements were taken in the vertical plane of symmetry of the truck for two values of the gap between tractor and trailer:

- •12 cm corresponds to the point of initial rise of trailer drag
- •16 cm corresponds to the point of highest drag on trailer

# 12 cm gap



# 16 cm gap



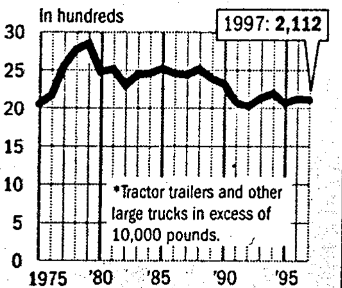
LATIMES
DATE ?

LA TIMES MAY 26, 1999

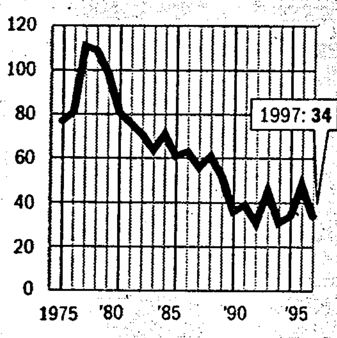
## Cars vs. Trucks

The nation's highways have become safer for just about everybody except people in passenger vehicles that collide with trucks.

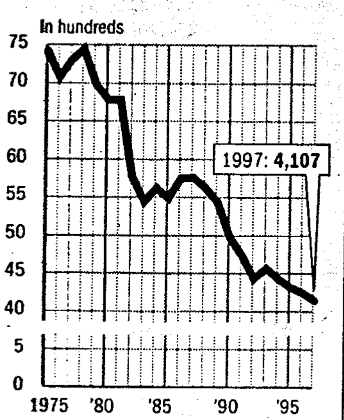
More than 2,100 car drivers and passengers died in 1997 in accidents involving trucks*, about the same number as in 1975.




Meanwhile, the number of truckers killed in crashes with cars plunged by more than half...




... and the number of people killed in crashes between two cars declined by more than two-fifths.




Source: National Highway Traffic Safety Administration

Los Angeles Times

UPDATE

# Plans Aimed at Halving Truck Fatalities Unveiled

By RICARDO ALONSO-ZALDIVAR
TIMES STAFF WRITER

WASHINGTON—Transportation Secretary Rodney Slater, responding to widespread criticism that his agency neglects truck safety on the nation's highways, Tuesday announced a program of stronger enforcement and technological innovation aimed at cutting crash deaths by half in the next decade.

But safety advocates and industry representatives questioned whether the program can achieve its intended goal. And safety advocates argued that it does nothing to change what they see as a cozy relationship between the trucking industry and its regulators. The lukewarm reaction increased prospects that Congress will tackle truck safety in coming months.

About 5,300 people now lose their lives in accidents involving large trucks each year, with more than three-fourths of the victims in passenger vehicles. In California, 409 people were killed in truck crashes in 1997, the latest year for which statistics are available.

Slater pledged that the department would reduce the national death toll to fewer than 2,700 lives a year, an ambitious goal that, he said, "will require us to change our thinking." But safety advocates, industry representatives and even some Transportation Department officials wondered whether the goal is real—as Slater insisted—or a sound bite.

"Ten years from now, [Slater] is not going to be here," said one department official involved in safety issues, who declined to be identified. "It would have been more dramatic if he had said we're going to reduce it by 20% next year and started shutting down firms that are in violation."

Among the measures Slater announced Tuesday: more inspections, higher fines, more federal truck safety inspectors at the Mexican border and an effort to speed up new rules to prevent driver fatigue—a project bogged down for a decade.

He also pledged an aggressive study of the latest technological innovations that would improve truck safety. The department is looking at recorders that automatically document hours driven, allowing regulators to enforce limits and prevent overworked drivers from falling asleep at the wheel. And it also is looking at speed-limiting devices that prevent trucks from being driven too fast. Some companies already use such devices.

Addressing the recent collision of an Amtrak train and a truck at an Illinois rail crossing, Slater proposed stricter licensing requirements and a new regulation that would bar drivers who try to beat a railroad signal from holding commercial licenses.

His plan calls for $56 million in additional federal truck safety spending—a 37% increase. But it is unclear whether Congress would agree to divert the money from other programs.

Yet the proposal left a critical issue unaddressed:

Safety advocates, industry representatives, members of Congress and the Transportation Department inspector general all have called on Slater to move the federal truck safety agency—the Office of Motor Carriers—out of its current bureaucratic home in the Federal Highway Administration, whose primary mission is not truck safety but road building.

Safety advocates want it placed in the National Highway Traffic Safety Administration, while the industry wants a separate agency modeled on the Federal Aviation Administration.

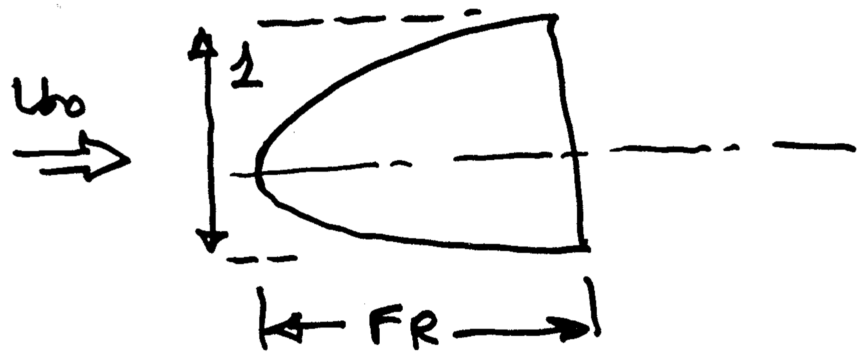
"There is no credibility in the existing agency," said Rep. Frank R. Wolf (R-Va.), who chairs a transportation funding panel in the House. While pleased with the new emphasis on enforcement, Wolf noted that it would make up only for cuts in inspections in recent years. The department acknowledged that Slater's plan merely would return the number of inspections to the 1992 level.

The American Trucking Assns., an umbrella trade group, said that it welcomes additional enforcement and wants to work with the government to weed out unsafe trucking companies. But spokesman Mike Russell said that he believes the industry is being unfairly singled out.

"There's an attitude about trucking that has resulted in a blanket indictment of all motor carriers," he said. "In fact, safety is No. 1 on the list when our people are on the job."

# MINIMUM $C_D$ FOR BODY WITH BLUFF BASE

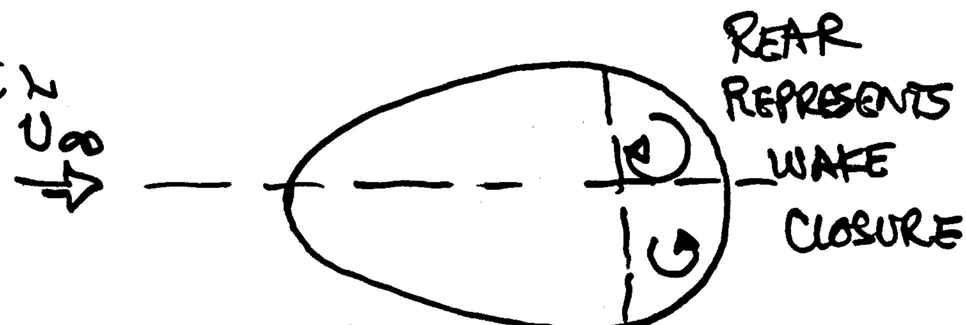
- ELLIPSOID




- DRAG CONTRIBUTIONS

| | |
|---|---|
| PRESSURE DRAG OF FOREBODY | $C_D$ FOREBODY |
| PRESSURE DRAG OF BASE | $C_D$ BASE |
| SKIN FRICTION | $C_{Df}$ |

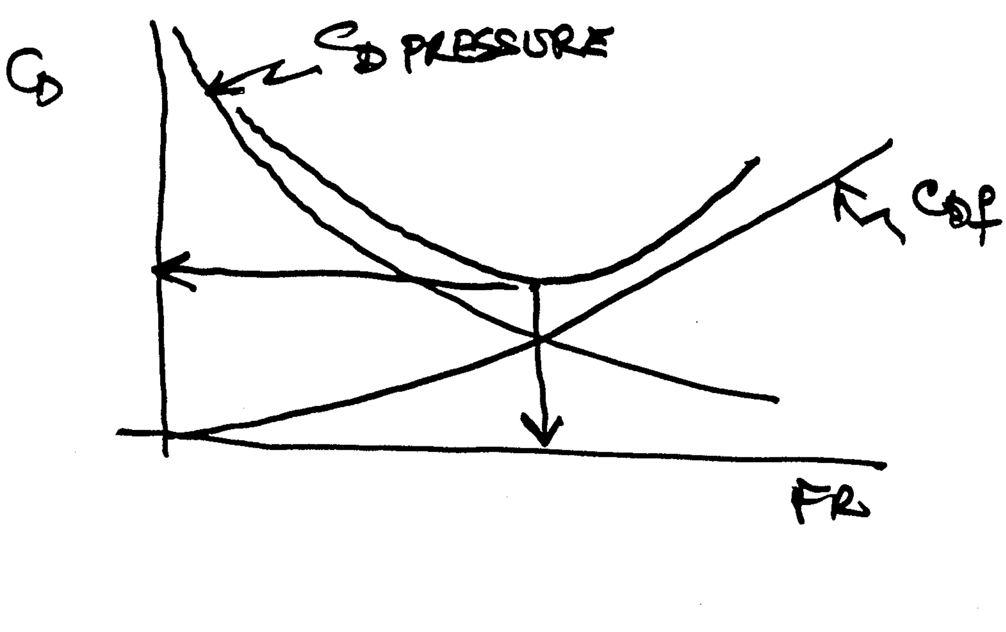
- FLOW MODEL




$C_{D\,FOREBODY}$ → POTENTIAL FLOW OVER "EGG"

$C_{D\,BASE} = C_{P\,BASE} A_{BASE} \cong \left(1-\left(\frac{U_1}{U_\infty}\right)^2\right) A_{BASE}$

$C_{Df}$ ⇒ BL ESTIMATE



# Analyzing and Reducing Aerodynamic Drag of Class 7-8 Trucks, DOE R&D Program

Kambiz Salari

Walter H. Rutledge

Aerosciences and Compressible Fluid Mechanics Department

Sandia National Laboratories

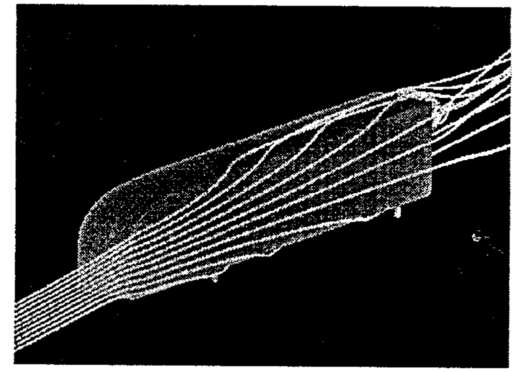
July 30, 1999

Sandia National Laboratories

# Projected Sandia Milestones, FY99-FY00

FY99

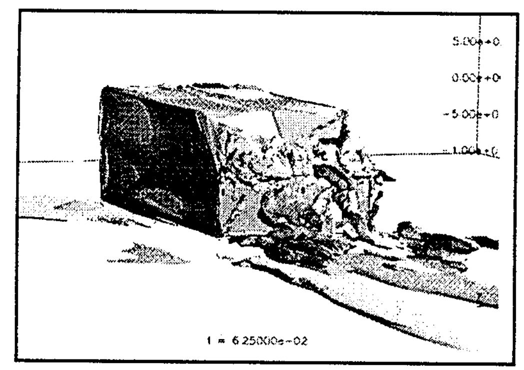
- High Reynolds number RANS Calculations
- Comparison with Texas A&M 7'x10' test
- Begin working with NASA/ARC 7'x10' test
    - Investigate proper inflow B.C.
- Initiate tractor-trailer gap and height mismatch study
- Initiate incorporation of LES into SACCARA



RANS computation, GTS model

FY00

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



LES Calculation, Ahmed body

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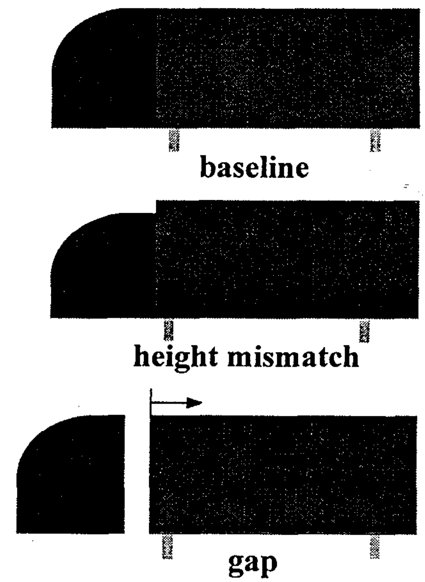
# Leveraging from Other R&D Programs

- DOE ASCI Aerodynamics program
  - RANS Code Development (SACCARA)
  - Intel Teraflop access time
  - Verification & Validation
- Sandia Engineering Sciences Research Foundation (Tech Base, LDRD)
  - Transition and Turbulence Modeling
  - LES Development
  - DES Research
- Potential BASF CRADA
  - LES Development & Application

# Sandia Near-Term Goals

Sandia Model, GTS

- **Experimental Data**
  - Texas A&M 7'x10', 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
  - NASA 12', Re= 5,000,000 ???
- **Computational Activities**
  - RANS/LES for high and low Re (Baseline)
  - Height mismatch and gap study at low Re (USC data) ???
  - Height mismatch and gap study at high Re (NASA data?)




Navistar's Model for Re sensitivity study

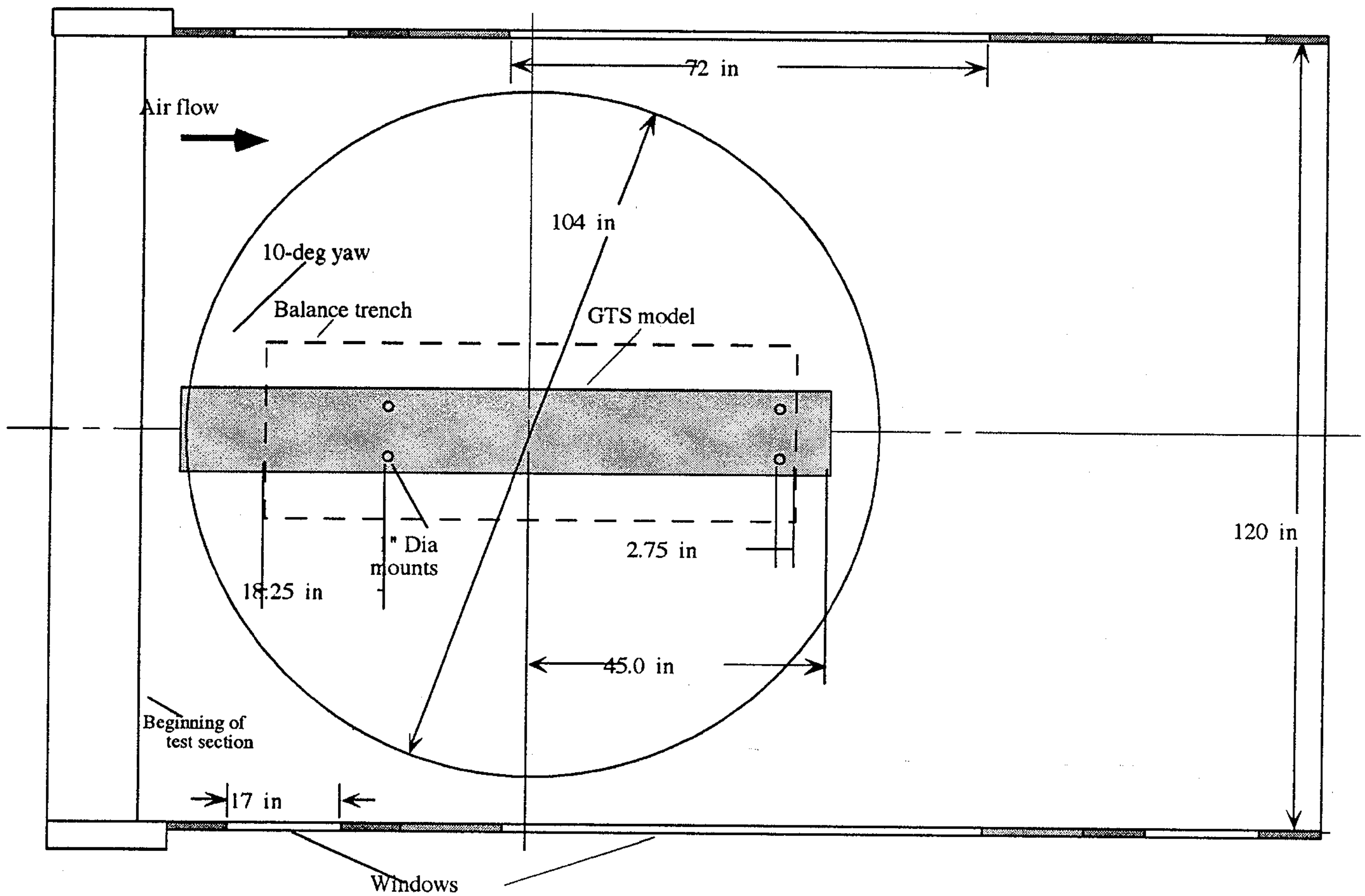
- **Participate in NASA 12' wind tunnel experiment**
  - $Re_{max}$ = 5,000,000, model with/without components

# NASA ARC 7'x10' Test Summary

- Principal measurements (Status of Data?)
  - Drag and discrete pressure measurements
  - Pressure-Sensitive Paint (PSP)
  - Unsteady pressure (one point)
  - Skin friction (oil film interferometry)
  - Particle Imaging Velocimetry
  - Transition (surface hot films)

# GTS Model Installation at NASA 7'x10' (Inflow & Side Wall B.C.s?)

Top View




GTS Model: Ames 7x10 Installation

Scale: 1" = 1.75'

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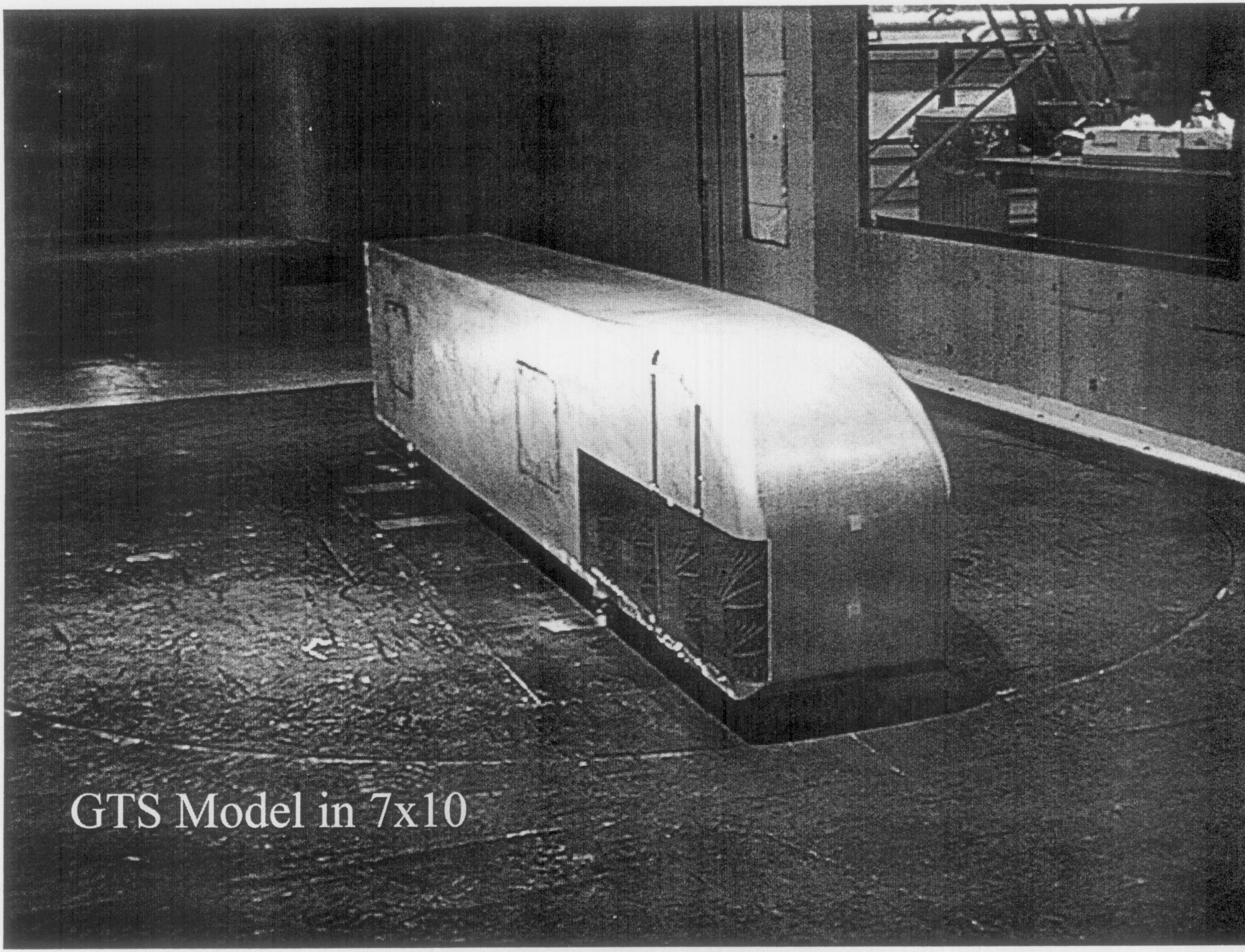
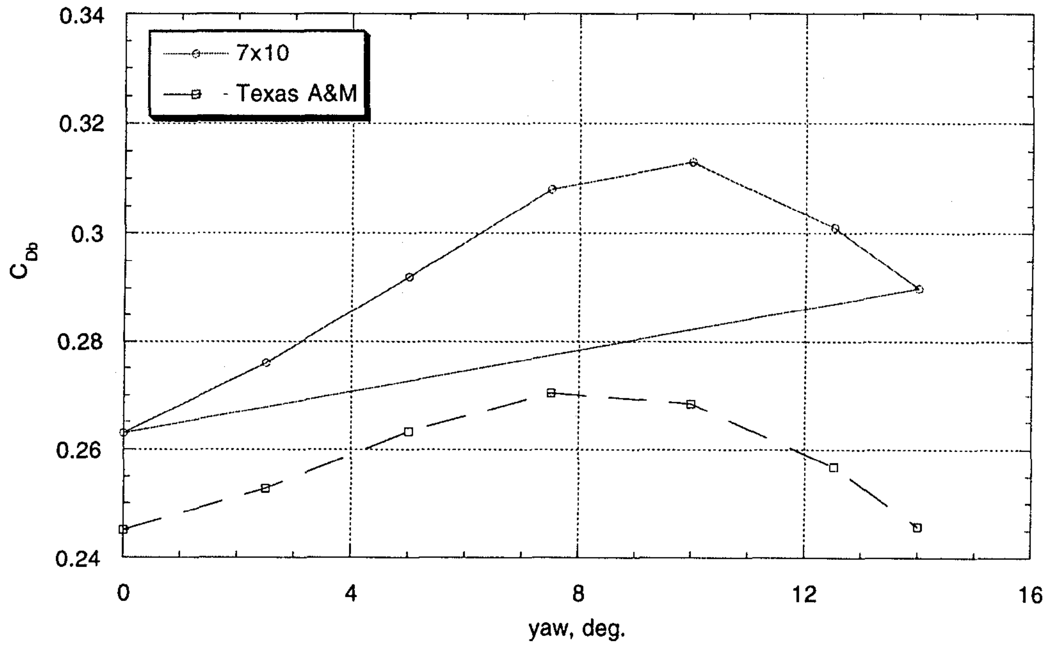

GTS Model in 7x10

# Comparison of NASA ARC 7'x10' and Texas A&M 7'x10' Drag Results




Differences

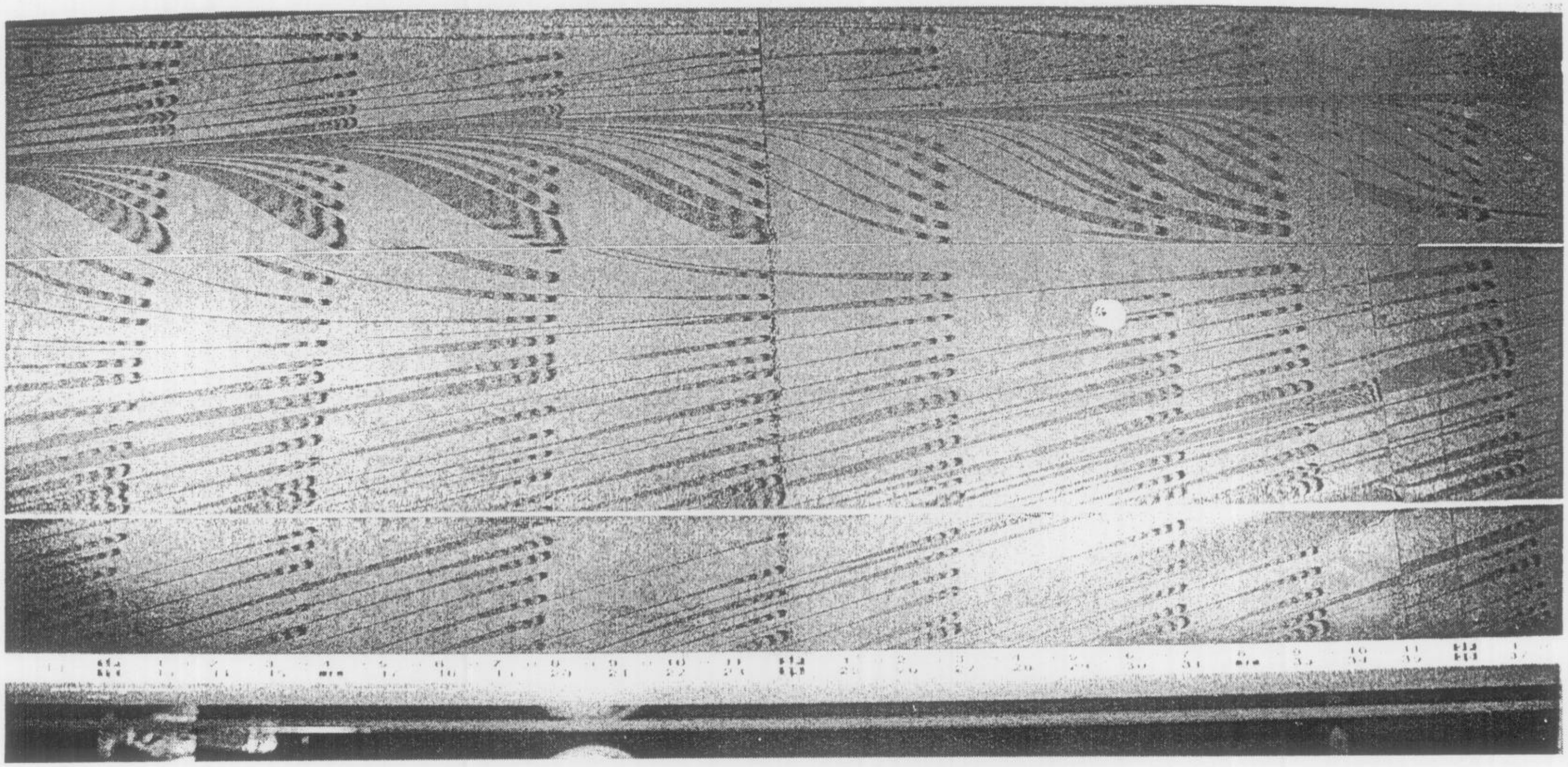
- Corrections applied at Texas A&M?
- Location of static reference pressure ring

- Status? (Who is investigating this problem?)

# Oil film image

Top view of trailer at 10° yaw

V



Skin friction is proportional to fringe spacing

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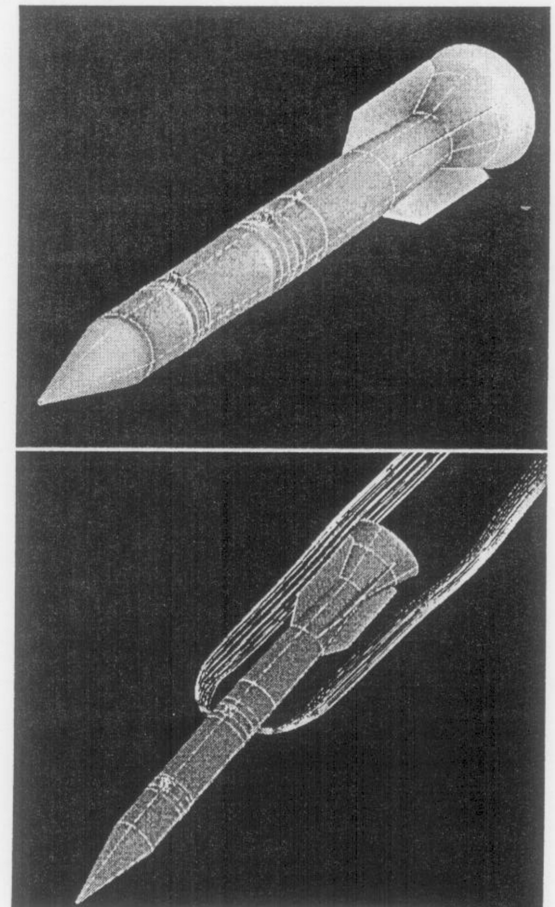
# SACCARA Code Capabilities

Sandia Advanced Code for Compressible Aerothermodynamics Research and Analysis

- Multi-block, structured grids for 2-D, Axisymmetric, and 3-D flows
- Solution of the Full Navier-Stokes equations for compressible Flows
- Finite volume spatial discretization (steady and unsteady)
- MP implementation on a variety of distributed parallel architectures (IBM, Intel, etc.)
- Implicit time advancement schemes
- Subsonic → Hypersonic flows
- Zero-, one-, and two-equation turbulence models
- Ideal, equilibrium, and thermo-chemical nonequilibrium finite-rate gas chemistry
- Ablation boundary conditions
- Rotating coordinate system



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# GTS Flow Simulation, Texas A&M Test

Test Condition for run 31, no wheels:

- $Re = 1.6 \times 10^6$
- Yaw angle = 0° and 10°
- Free stream velocity = 78 (m/s)
- Free stream Mach number = 0.23
- Density = 1.17 ($kg/m^3$)
- Static Pressure = 99,470.6 (Pa)
- Kinematic viscosity = $1.555 \times 10^{-5}$ ($m^2/s$)

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# Matrix for Grid Convergence Study

| Yaw Angle | Grid Size | | |
|---|---|---|---|
| | Coarse | Medium | Fine |
| 0 | X | X | In Progress |
| 10 | X | X | In Progress |

Coarse Mesh: 0.5 million nodes, 107 processors

Medium Mesh: 4 million nodes, 246 processors

Fine Mesh 32 million nodes, 1400 processors

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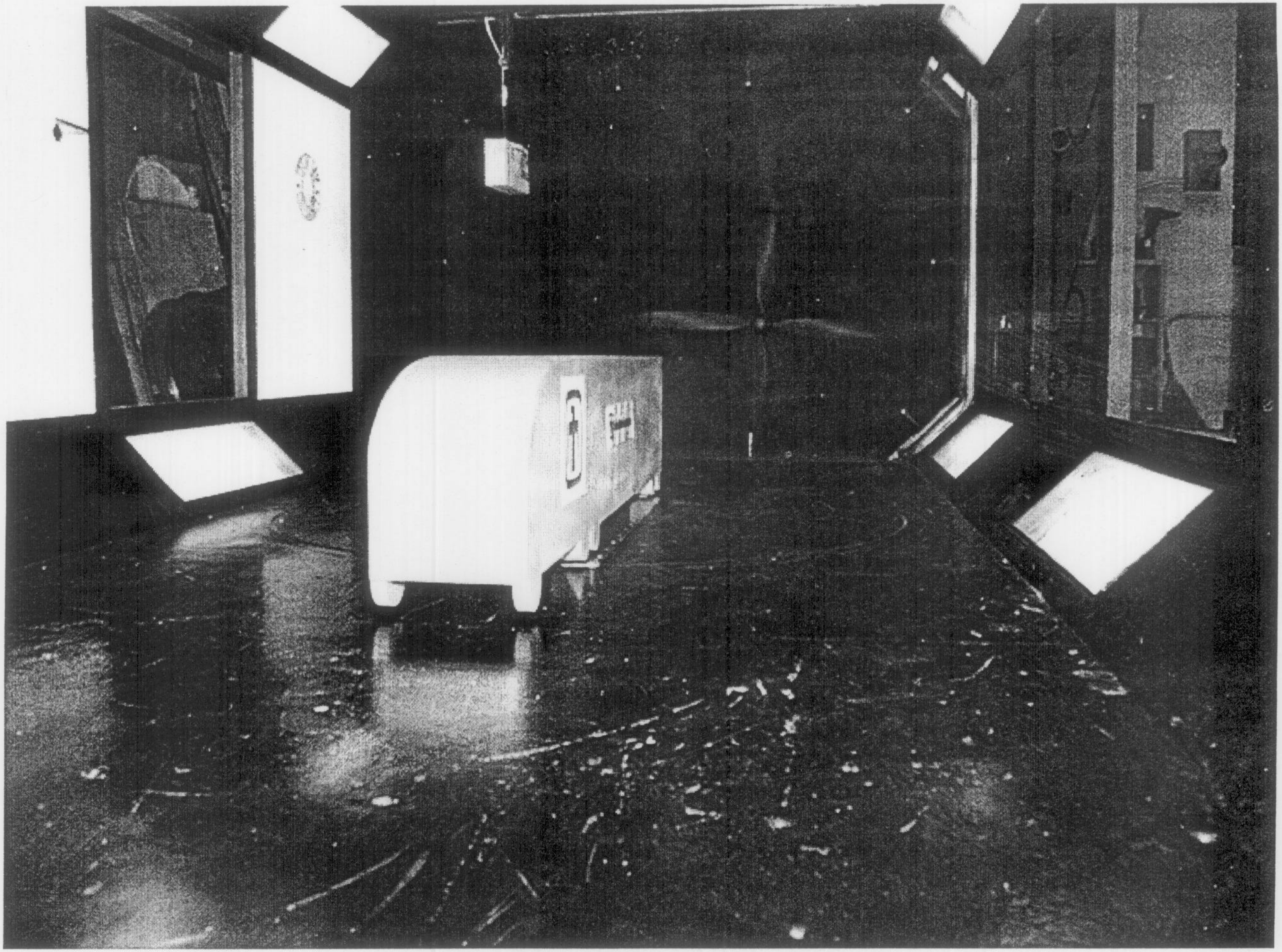
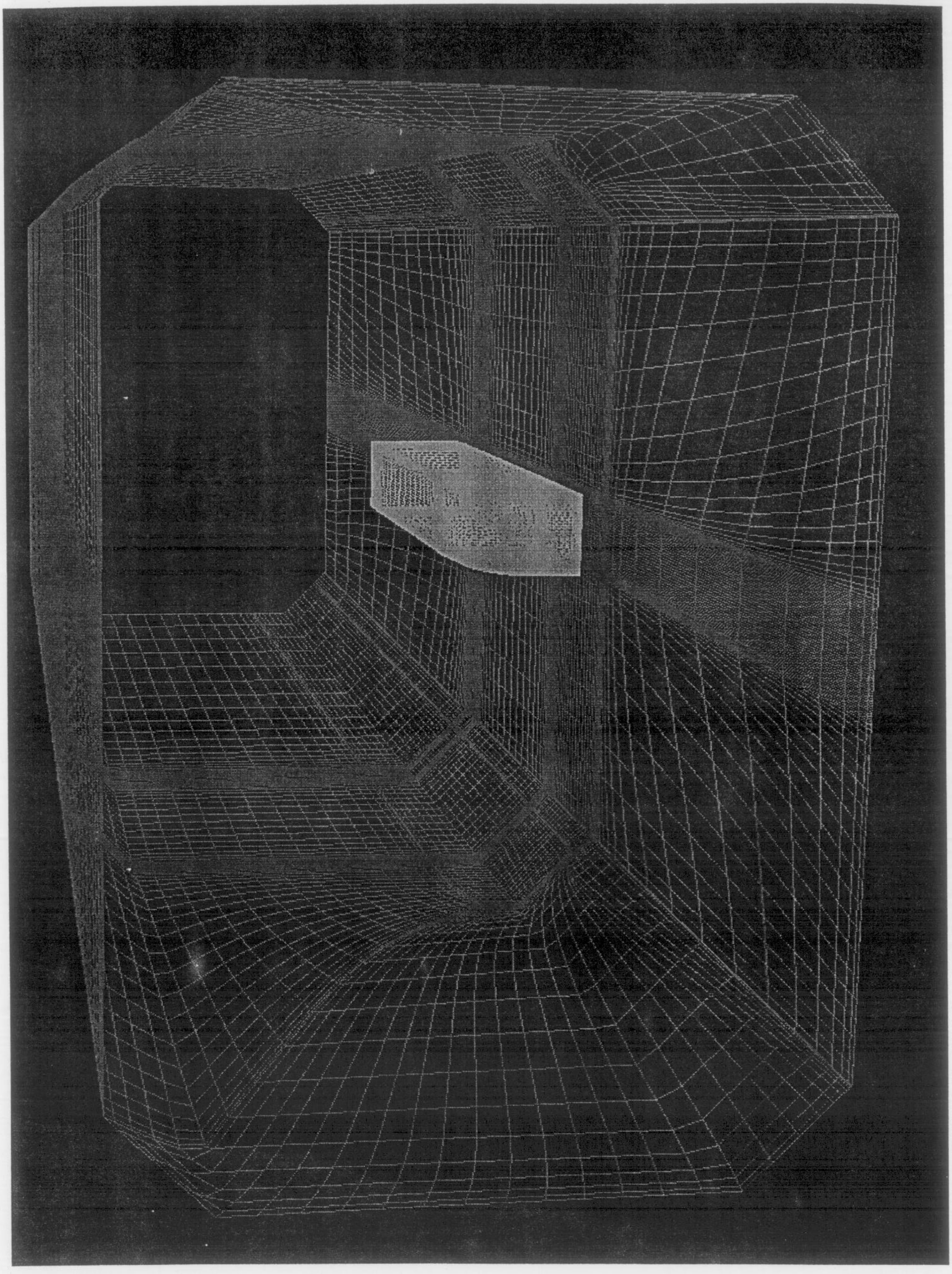
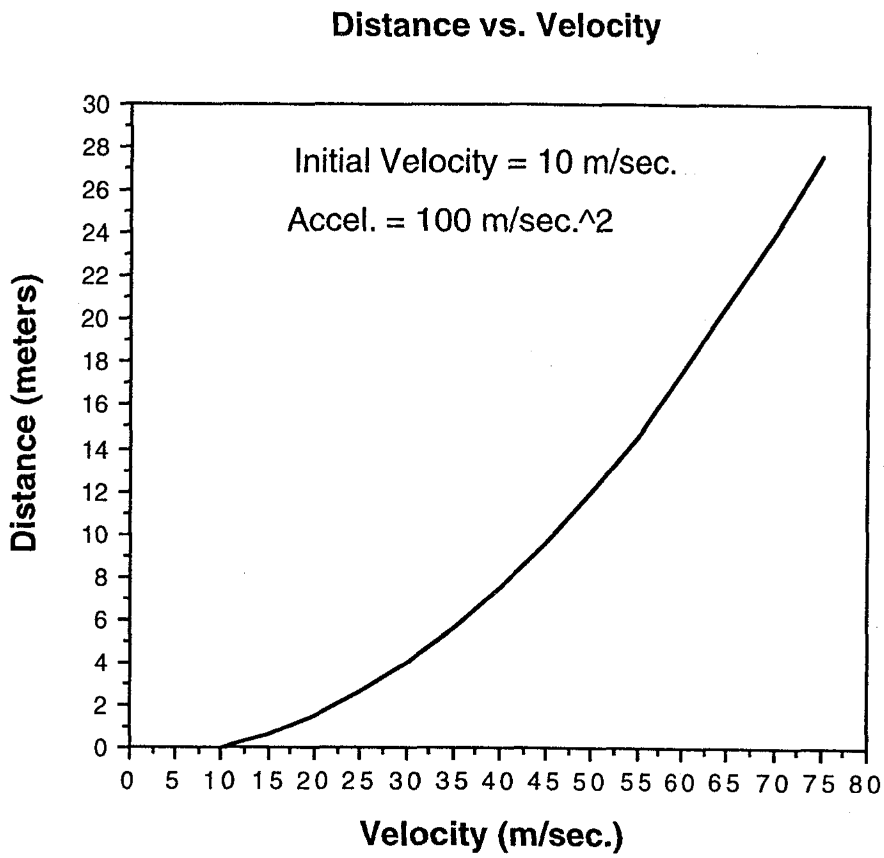
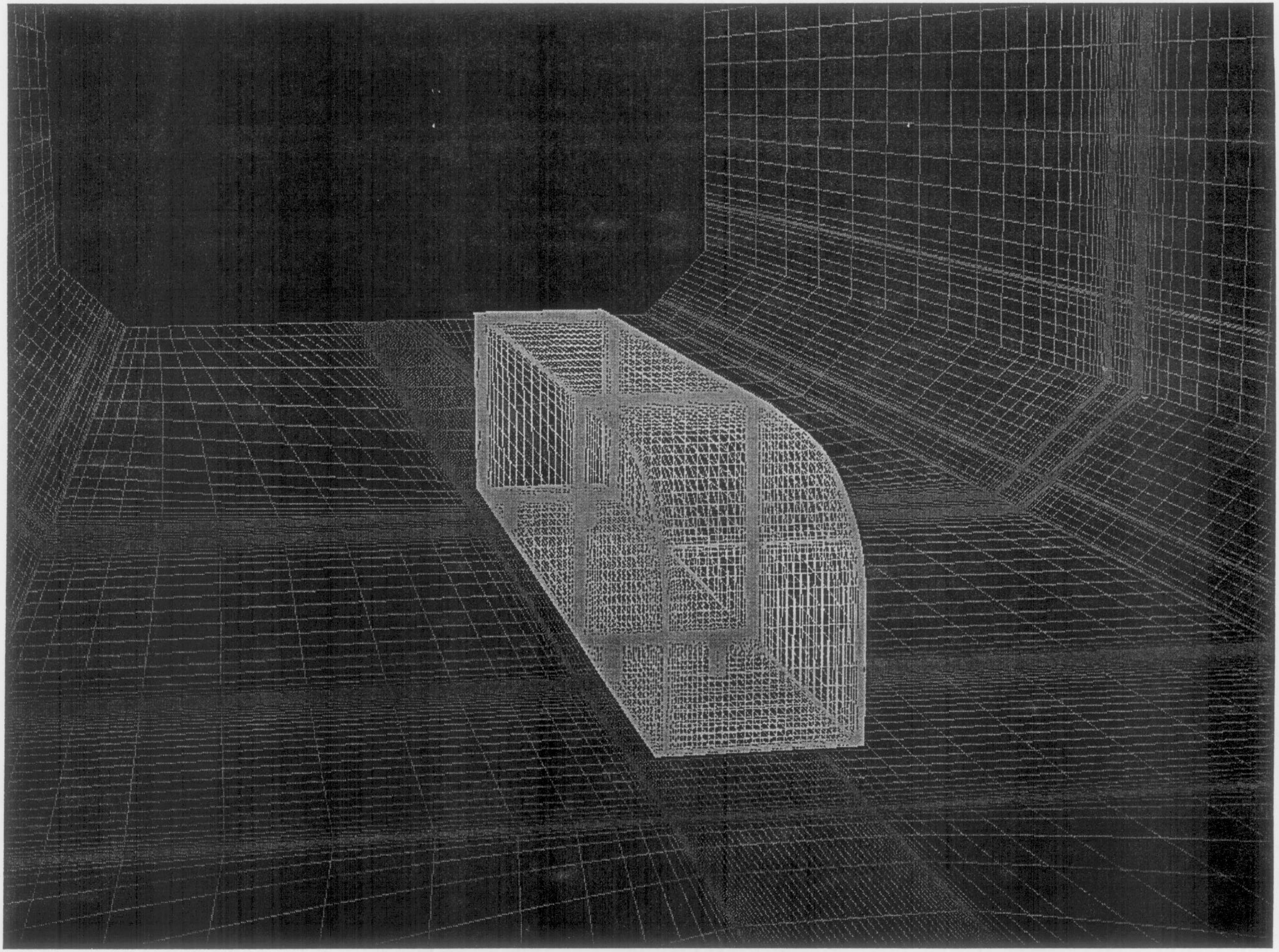


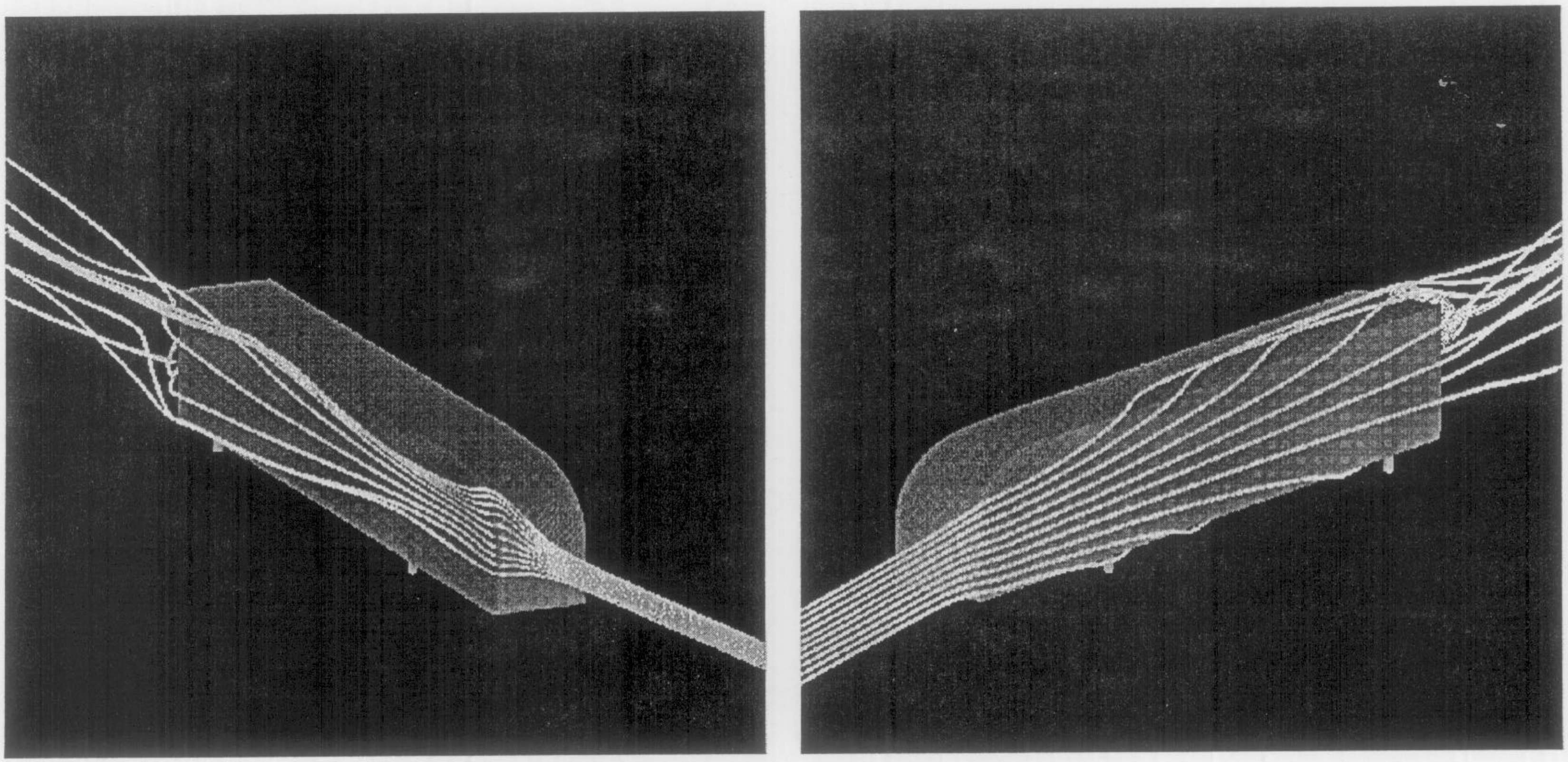



Distance vs. Velocity
Initial Velocity = 10 m/sec.
Accel. = 100 m/sec.^2
Distance (meters)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Velocity (m/sec.)



# GTS Flow Simulation

10° yaw, Medium mesh, Particle traces are colored by velocity magnitude



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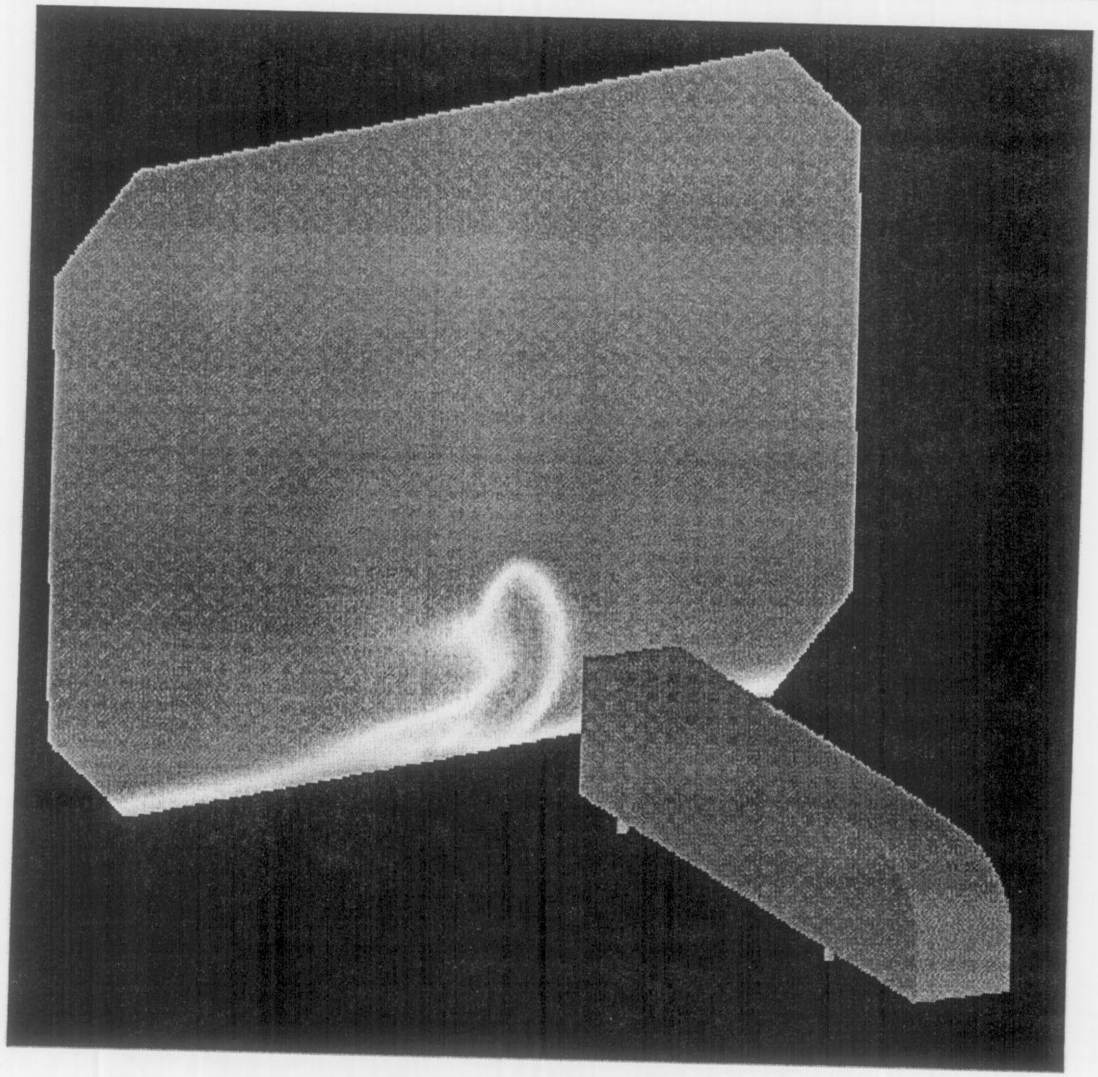
# GTS Flow Simulation

10° yaw
x-plane cut
Mach contours



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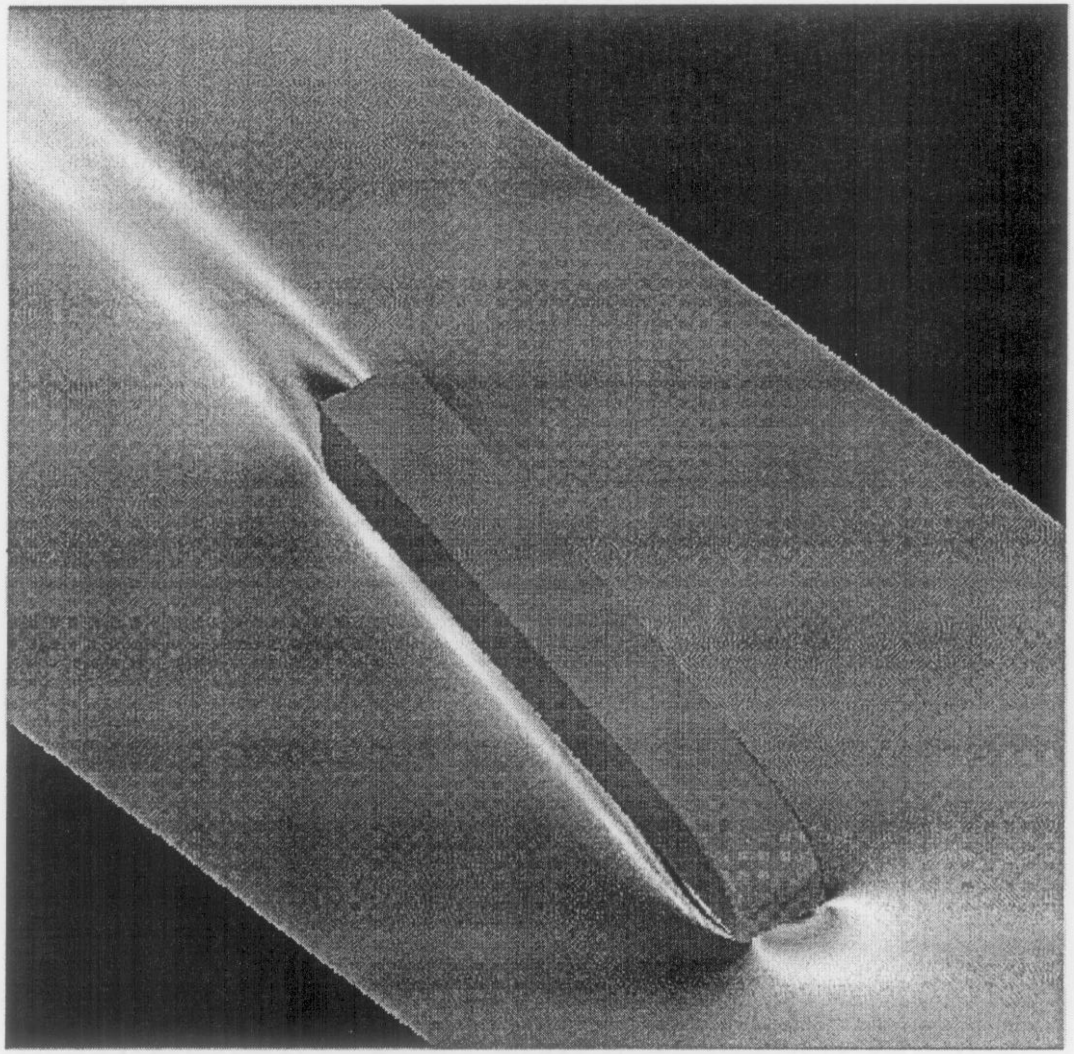
# GTS Flow Simulation

10° yaw
y-plane cut
Mach contours



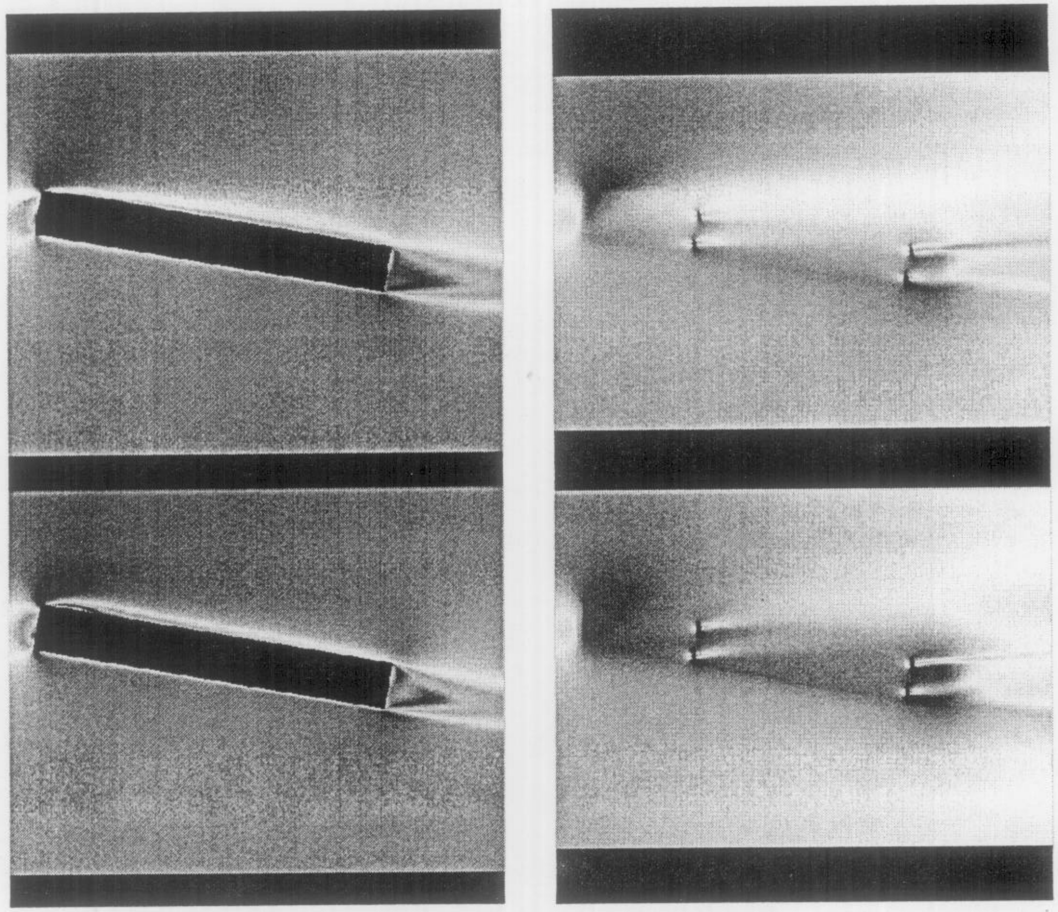
# GTS Flow Simulation

10° yaw
y-plane cut
Mach contours

y = 0.122 m — y = -0.035 m

Coarse

Medium



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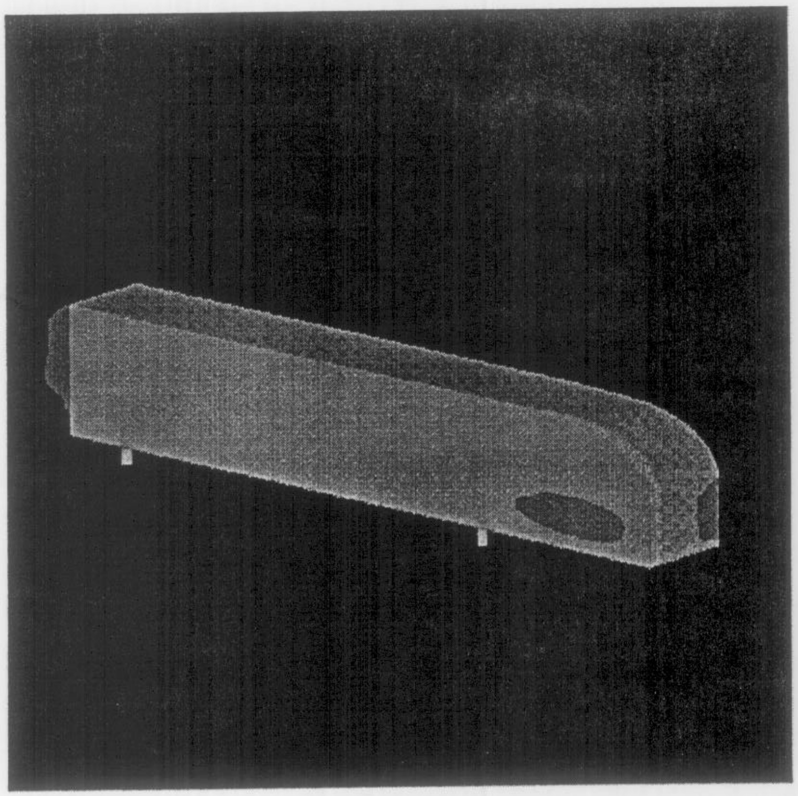
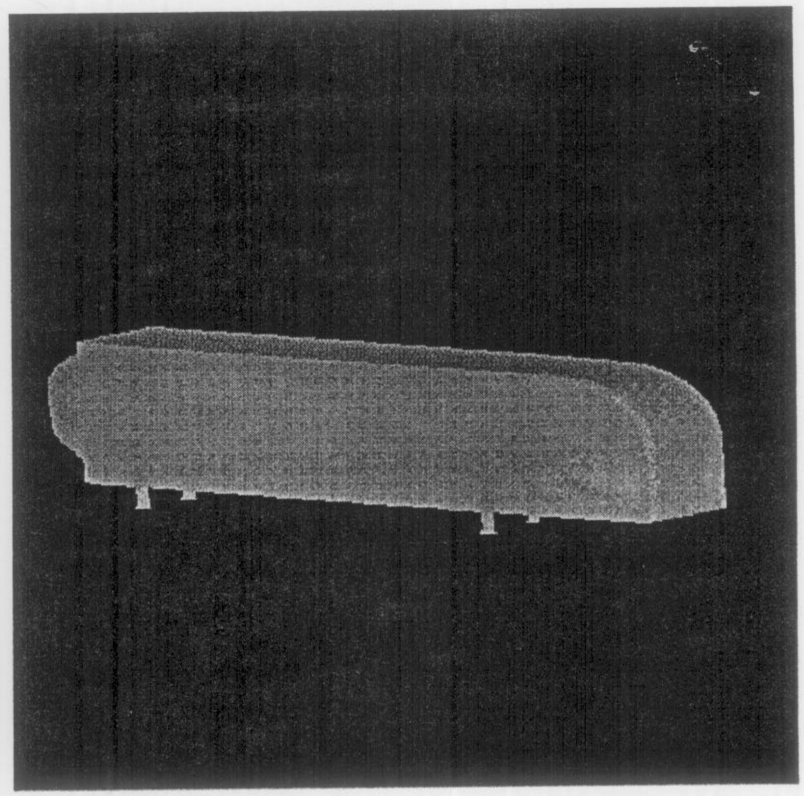
# GTS Flow Simulation

10° yaw, IsoSurface u = -0.001 (m/s)

Coarse



Medium



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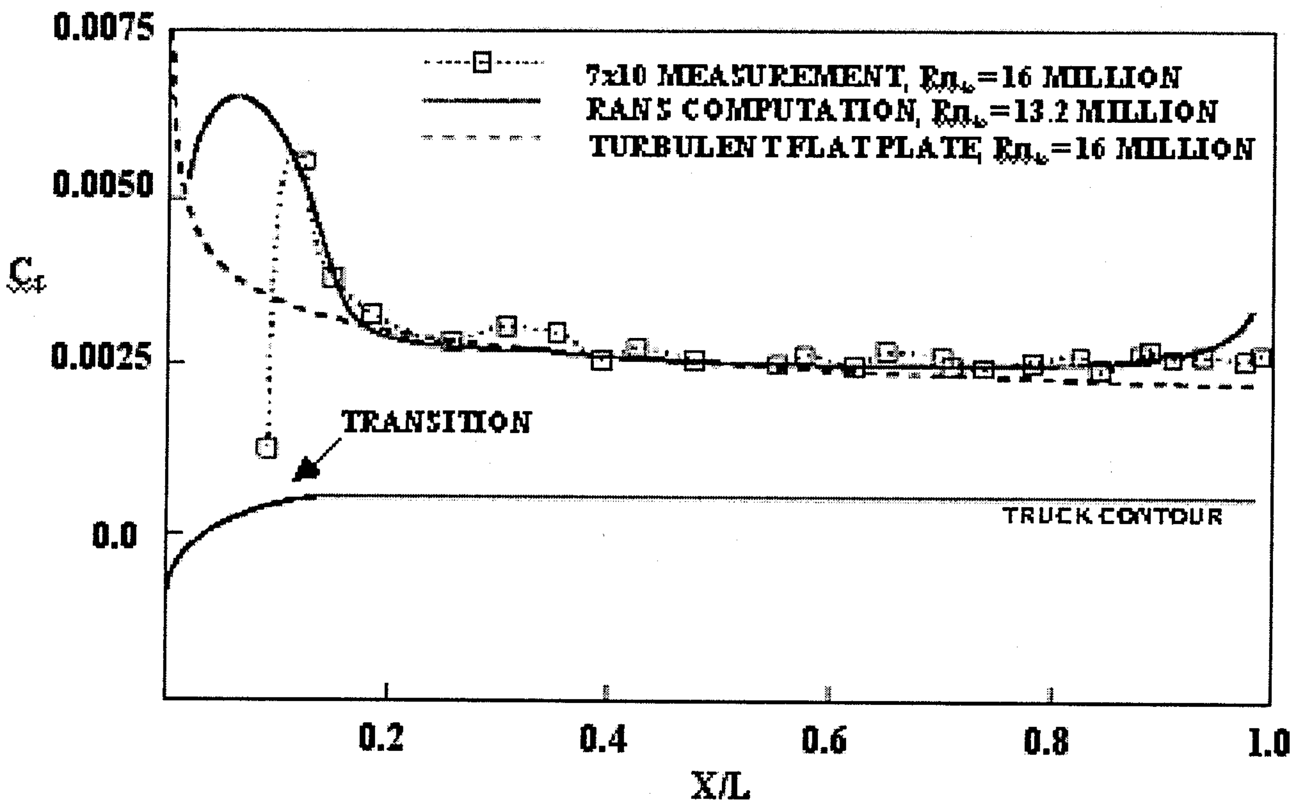
# Skin Friction Comparison NASA Experiment

Greg Zilliac, Dave Driver, NASA ARC

0° yaw, top surface, center line



# Sandia Future Plans

- Finish the fine grid solutions and compare to the experimental data of Texas A&M
- Setup new grids for GTS model with/without the boattail plates in the NASA ARC 7'x10' tunnel
- Run simulations with/without boattail plates and compare to the 7'X10' NASA experimental data
- Run simulations for gap study and compare to the Low Re USC experimental data (GTS Geometry)??
- Run Large-Eddy Simulations for the 7'X10' NASA test
- Run simulations for gap study and compare to future High Re NASA 12' tunnel experimental data (GTS Geometry)??

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# ASCI Mechanics Codes: Modeling and Simulation

- Goal: "Software is a product"
  - Terascale Production Computing
  - Input: Solid Model Definition and Grid Generation
  - Mechanics Code: Massively Parallel
  - Output: Terabytes of graphics information piped to a workstation environment
    - But how to interpret this amount of information?
  - SQA
  - V&V, and UQ

# Verification, Validation, and Uncertainty Quantification

- Should be required for Production Codes used in industry
- Will be required for DOE Weapons Applications
- Verification: "Solving the equations correctly?"
- Validation: "Are we solving the correct equations?"
- Uncertainty Quantification: Quantitatively, "how good is good enough?"
  - Experimental as well as Computational
- AIAA CFD V&V Guide plus SNL V&V/UQ ref.s

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# The Six Recommended Practices of a "Validation Experiment"

- Validation experiment should be jointly designed and executed by experimentalists and code developers
- Validation experiments should be designed to capture the relevant physics, all initial and boundary conditions and auxiliary data (viscosity, flow rates, etc.)
- Validation experiments should utilize any inherent synergisms between experiments and computational approaches (try to offset strengths and weaknesses between the two)

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# The Six Recommended Practices of a "Validation Experiment" (cont'd)

- The flavor of a blind comparison of computational results with experimental data should be a *goal* (that is, it should be an attempted to be a true prediction not a code calibration)
- Level of complexity of physics should be attacked in a *series* of validation experiments (start off simple with experiments at high confidence and work up to more complex flows, e.g., turbulent flows)

# The Six Recommended Practices of a "Validation Experiment" (cont'd)

- Develop and employ experimental uncertainty analysis procedures to delineate and quantify systematic and random sources of errors
- Reference: Oberkampf and Aeschliman, AIAA Journal, May 1998, pp. 733-741.
- Reference: AIAA Guide to Verification and Validation of Computational Fluid Dynamics

# VIPAR
## Sandia's Unsteady Fluid Mechanics Code

- New ASCI Teraflop scale code for "compressible, unsteady fluid mechanics"
- Coupled fluid/structures interaction
- Initially incompressible
- Based on vortex methods (Strickland, Kempka)
- Working towards viscous, compressible for high-speed (supersonic) parachute inflation and deceleration events...

Truck Aerodynamics:

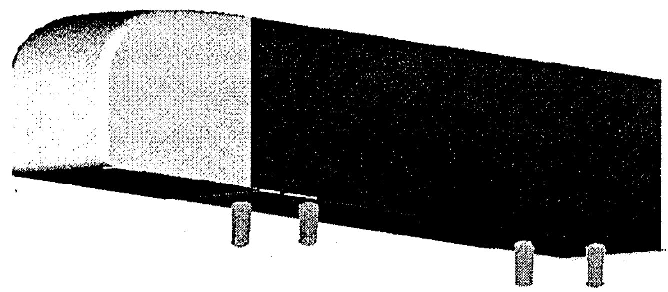
# Large-Eddy Simulation (LES) using the Finite-Element Method (FEM)

Rose McCallen and Dan Flowers
Lawrence Livermore National Laboratory

July 1999

University of California
Lawrence Livermore National Laboratory

# Incompressible and compressible flow modeling is needed for comparison to experimental results.



| Experiments | | | Computational Time-Step Constraint (explicit, 1-mm grid scale) |
|---|---|---|---|
| **Compressible (Ma > 0.1)** | | | |
| NASA 7'x10' | Re = 2,000,000 | Ma = 0.27 | $\Delta t \leq \frac{\Delta x}{2c} < O(10^{-6})$ |
| Texas A&M | Re = 1,600,000 | Ma ~ 0.2 | |
| **Incompressible (Ma < 0.1)** | | | |
| NASA 7'x10' | Re ~ 740,700 | Ma = 0.1 | $\Delta t \leq \frac{\Delta x}{2u_{local}} < O(10^{-5} - 10^{-2})$ |
| USC | 200,000 < Re < 400,000 | | |

# We have some preliminary results.

## Outline

### Incompressible Flow Model

Formulation changed

### Compressible Flow Model

ALE approach

LES/SGS model

### Simulations

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

| | |
|---|---|
| **Milestone** | **FY99 flow demonstration** |
| **R&D** | **Solver integration/parallelization**<br>**Turbulence modeling**<br>**Boundary conditions**<br>**Data analysis** |
| **Approach** | **Utilize existing methods, tools, resources, etc.**<br>- **Existing/tried formulation - changed**<br>- **Smagorinsky SGS model for FY99**<br>- **Integrating existing codes**<br>**Take advantage of the Lab's infrastructure** |

# Incompressible Flow

## The formulation had to change!

**Old**

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

**Solve for pressure**

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

**Update velocity**

$C^T M^{-1} C$ **--- solver interface could not form 'global' matrix multiply**

**New**

$$\frac{M}{\delta t}\underline{v} + CP = f \text{ where } \underline{v} = \underline{u}^{n+1} - \underline{u}^n$$

**Solve for pressure & velocity**

$$C^T \underline{v} = 0$$

**Constraint**

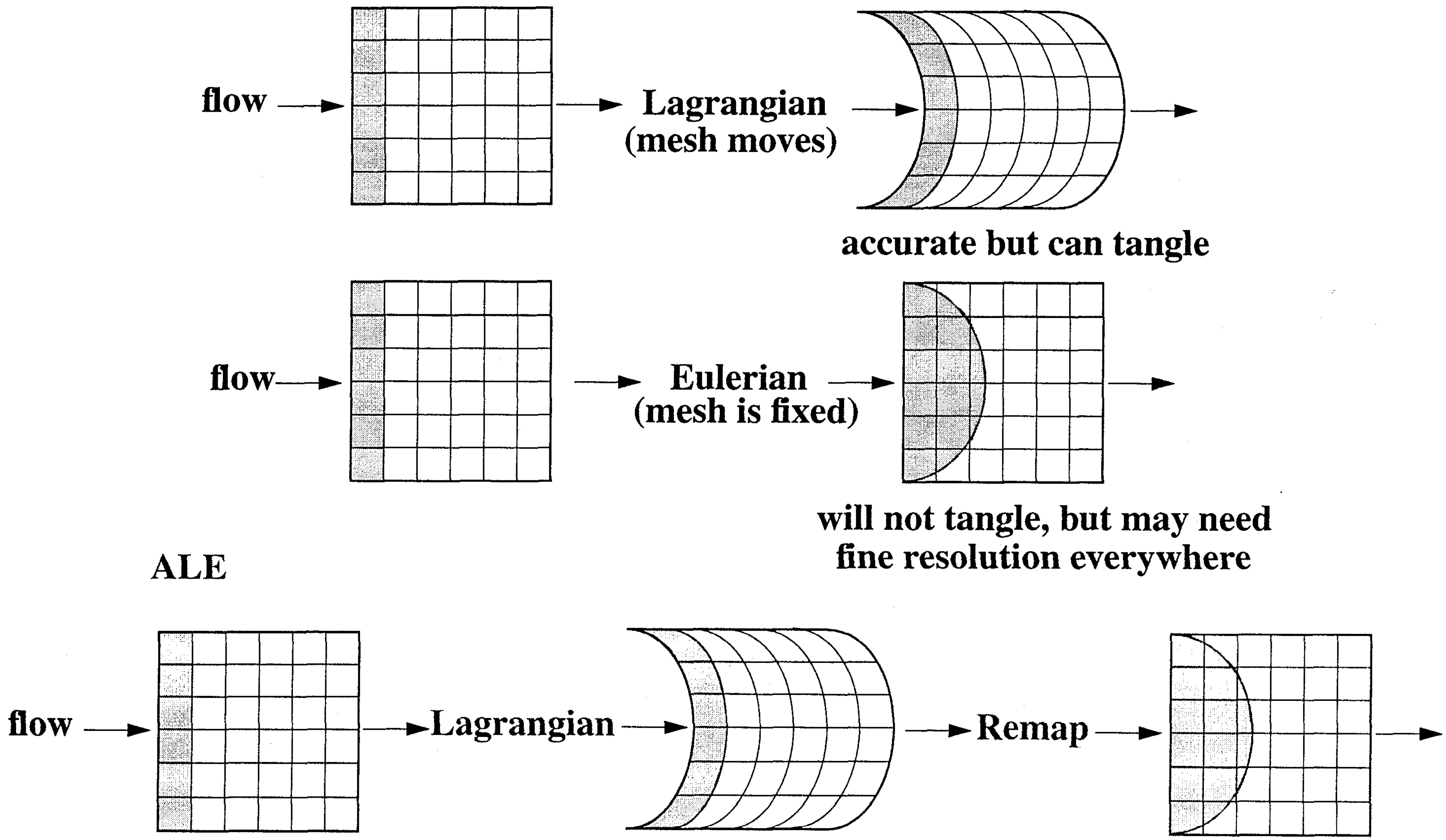
**where - for a fixed grid**

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

**C & M are only a function of geometry**

# Compressible Flow

## Arbitrary Lagrangian Eulerian multiphysics model



# Compressible Flow
## With FEM, the boundary conditions are built in.

**Momentum**

$$\int_{\Omega} \rho \ddot{x}_{\alpha} \phi_i + \int_{\Omega} \sigma_{\alpha\beta} \frac{\partial \phi_i}{\partial x_{\beta}^{j}} = \int_{\partial\Omega} \sigma_{\alpha\beta} n_{\beta} \phi_i$$

**Energy**

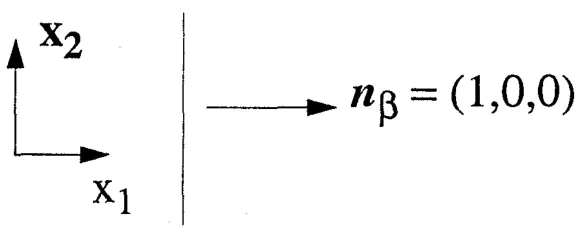
$$\dot{E} = -P\left(\frac{\dot{V}}{V_o}\right) + \left(\frac{V}{V_o}\right) \tau_{\alpha\beta} \frac{\partial u_{\alpha}}{\partial x_{\beta}}$$

**where**

$$\sigma_{\alpha\beta} = -\delta_{\alpha\beta} P + \tau_{\alpha\beta} \longleftarrow$$ **natural boundary conditions**

$$\tau_{\alpha\beta} = \mu\left(\frac{\partial u_{\alpha}}{\partial x_{\beta}} + \frac{\partial u_{\beta}}{\partial x_{\alpha}} - \frac{2}{3}\delta_{\alpha\beta}\frac{\partial u_{\gamma}}{\partial x_{\gamma}}\right)$$

**e.g.,**




$$f = \sigma_{\alpha\beta} n_{\beta} = (\sigma_{11}, \sigma_{12}, \sigma_{13}) \cdot (1, 0, 0) = \sigma_{11}$$

**= user specified constant**

# Compressible Flow

## For LES the filtered equations are solved.

**Decompose velocity field**

$$u = \tilde{u} + u'$$

**where** $\tilde{u}$: **resolved velocity**

$u'$: **subgrid-scale (SGS) velocity**

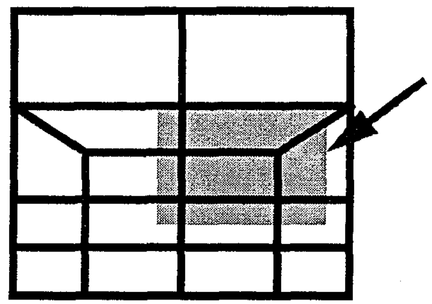
**Density weighted filter**

$$\tilde{u} = \frac{\overline{\rho u}}{\bar{\rho}}$$

**where** $\bar{f}(\underline{x}, t) = \int_{-\infty}^{\infty} G(\underline{x} - \underline{x}')f(\underline{x}', t)d\underline{x}'$ **and** $\int_{-\infty}^{\infty} G(\underline{x}, t)d\underline{x} = 1$

**Explicit filtering is not performed...**

**Problem:**
**FEM uses element-by-element formation with arbitrary connectivity**



**Filtering includes neighboring elements**

# Filtering results in nonclosed subgrid-scale terms that must be approximated (modeled).

**Momentum**

$$\int_{\Omega} \rho \ddot{\tilde{x}}_{\alpha} \phi_i + \int_{\Omega} (\tilde{\sigma}_{\alpha\beta} + \tilde{\sigma}_{\alpha\beta_t}) \frac{\partial \phi_i}{\partial x^j_{\beta}} = \int_{\partial\Omega} (\tilde{\sigma}_{\alpha\beta} + \tilde{\sigma}_{\alpha\beta_t}) n_{\beta} \phi_i$$

**Energy**

$$\dot{\tilde{E}} = -P\left(\frac{\dot{V}}{V_o}\right) + \left(\frac{V}{V_o}\right) \tilde{\tau}_{\alpha\beta} \frac{\partial \tilde{u}_{\alpha}}{\partial x_{\beta}} + \rho \frac{\partial \tilde{q}_{\beta_t}}{\partial x_{\beta}}$$

**Nonclosed SGS terms**

**Model (Leith, 1993)**

$$\tilde{\sigma}_{\alpha\beta_t} = L_{\alpha\beta} + C_{\alpha\beta} + R_{\alpha\beta} \cong R_{\alpha\beta} \cong \rho \upsilon_t S_{\alpha\beta}$$

**Terms neglected**

$$\upsilon_t = (C_s \Delta)^2 S,\ S = \left[S_{\alpha\beta} \frac{\partial \tilde{u}_{\alpha}}{\partial x_{\beta}}\right]^{\frac{1}{2}},\ S_{\alpha\beta} = \frac{\partial \tilde{u}_{\alpha}}{\partial x_{\beta}} + \frac{\partial \tilde{u}_{\beta}}{\partial x_{\alpha}} - \frac{2}{3} \delta_{\alpha\beta} \frac{\partial \tilde{u}_{\gamma}}{\partial x_{\gamma}}$$

**$\Delta$ is shortest grid length**

$$q_{\beta_t} \cong \bar{\rho} k_T \frac{\partial \tilde{e}}{\partial x_{\beta}},\ k_T = \frac{\nu_t}{Pr},\ Pr = \frac{\mu C_p}{k}$$

**Neglected**

# Truck Compressible Flow Results Using ALE3D-LES

Dan Flowers

Lawrence Livermore National Laboratory

Heavy Vehicle Aerodynamic Drag: Working Group Meeting

University of Southern California

July 30, 1999



Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

# Approach

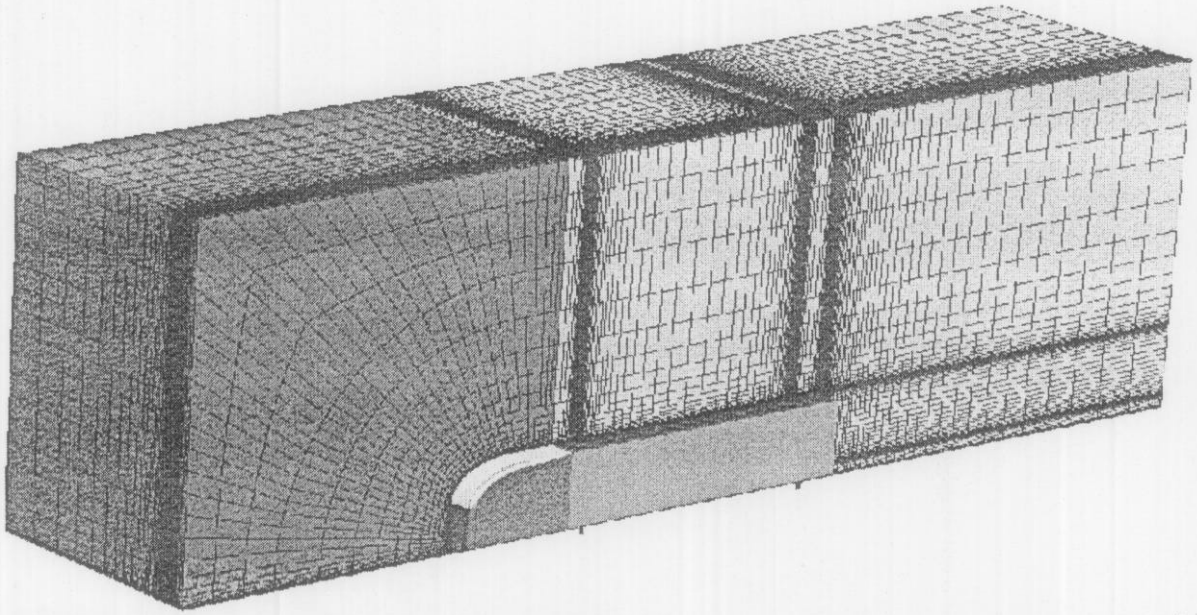
- The goal of this research is to develop methods to accurately predict aerodynamic drag on trucks
- Compressible flow simulation using ALE3D with SGS model are applied to solve 3D turbulent flow field
  - Full 3D geometry
  - Explicit solution - Courant limited time step
  - Parallel computation
- Currently simulating NASA wind tunnel experimental geometry

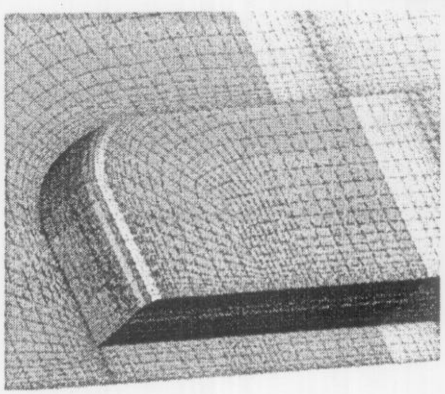
# Mesh generation

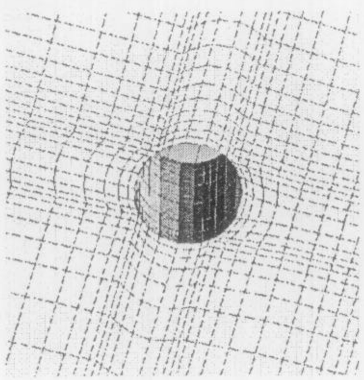
- The range of scales that need to be modeled for this problem are several orders of magnitude
- Unstructured (arbitrary connectivity) hexahedral mesh
- 900,000 elements for coarsest mesh
- Slip boundary conditions on side walls and upper surface of tunnel
- No slip on floor and truck surface
- Traction outflow condition
- Specified velocity inflow condition
- Curvature under front end is neglected for now (is being addressed in next generation mesh)

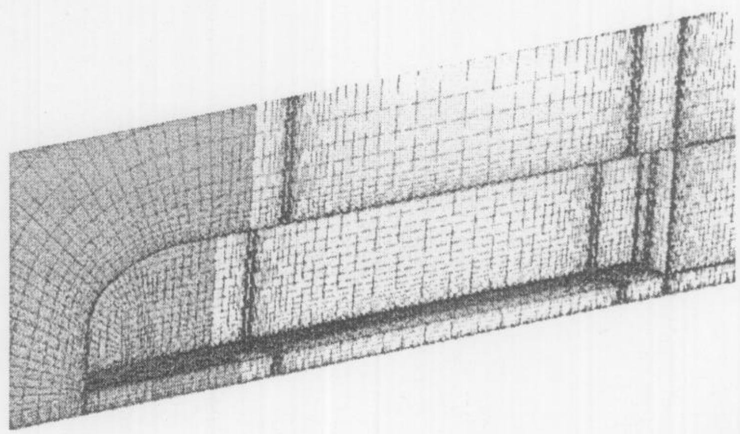
# Mesh generation

- 900,000 Element mesh with 2 mm wall resolution



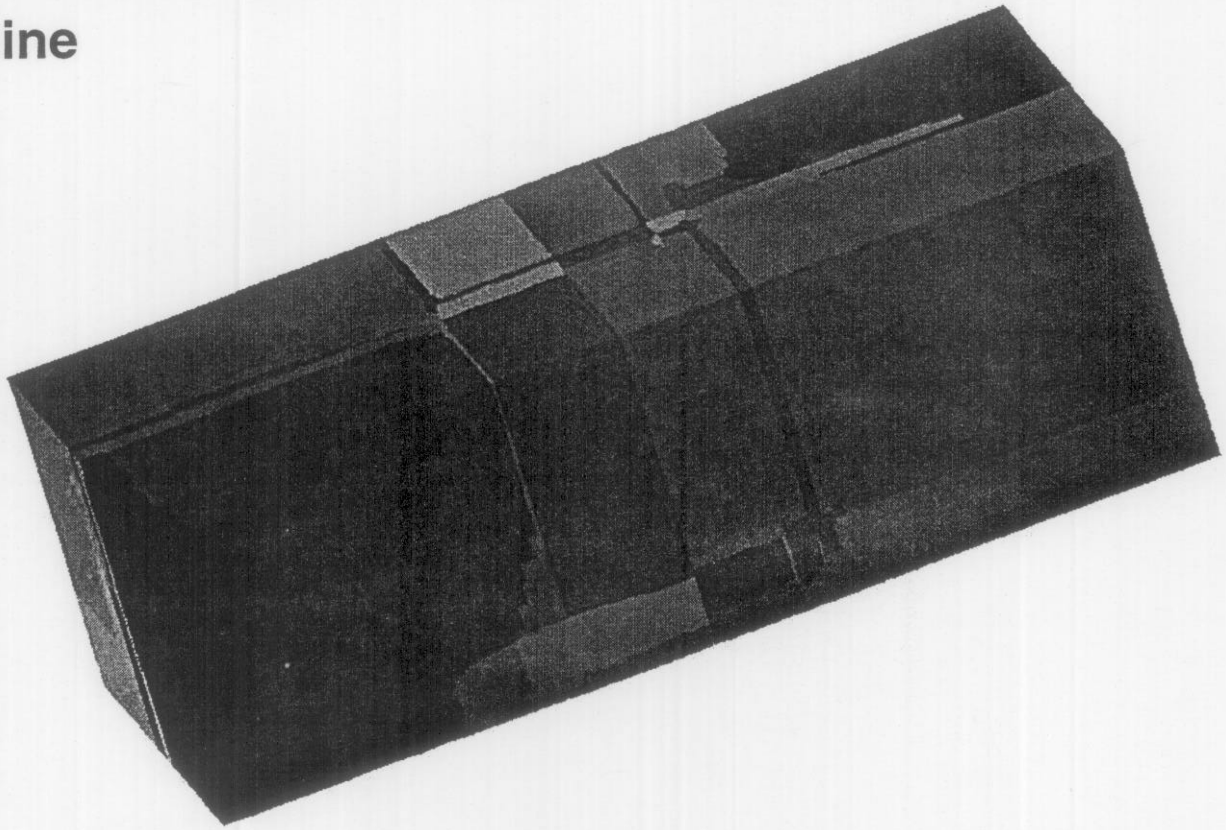






# Parallel Computation

- Parallel computation necessary because of large number of elements
- Decomposition into 128 computational domains using Metis algorithm
- Parallel computation using 128 processors on ASCI Blue massively parallel machine

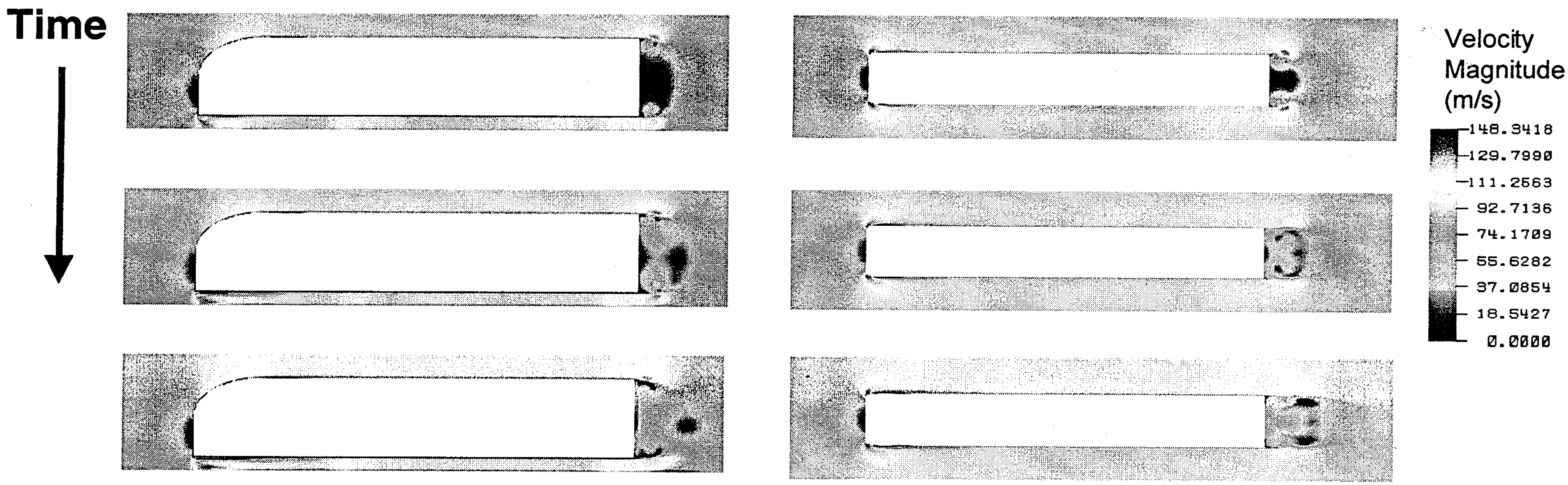


# Results

- Compressible flow simulation of the 7' x10' NASA wind tunnel tests for 0° yaw and Ma=0.27
- Courant time step limit is determined by shortest length across distorted elements along curved surfaces (0.2 $\mu$s time step for 2mm wall resolution)
- Results are for 40,000 time steps (8 ms simulated) requiring 30 hours of run time on ASCI Blue
- Run time may not be sufficient for startup effects to be eliminated
- Flow is still symmetric about the mid-plane of the truck - asymmetry may not have had time to develop
- Vortex shedding and separation phenomena are occurring

# Flow Field Near Truck

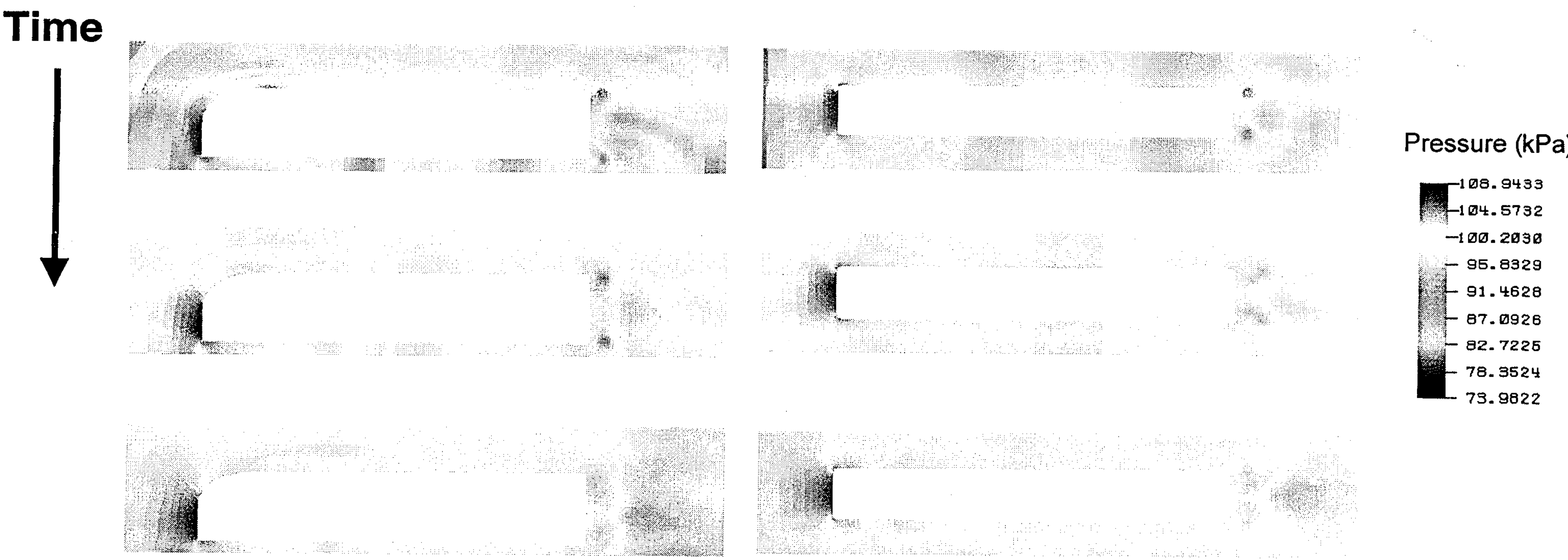
- **Strong recirculation can be seen to occur at the back end of the truck**




**Vertical Cut Plane** **Horizontal Cut Plane**

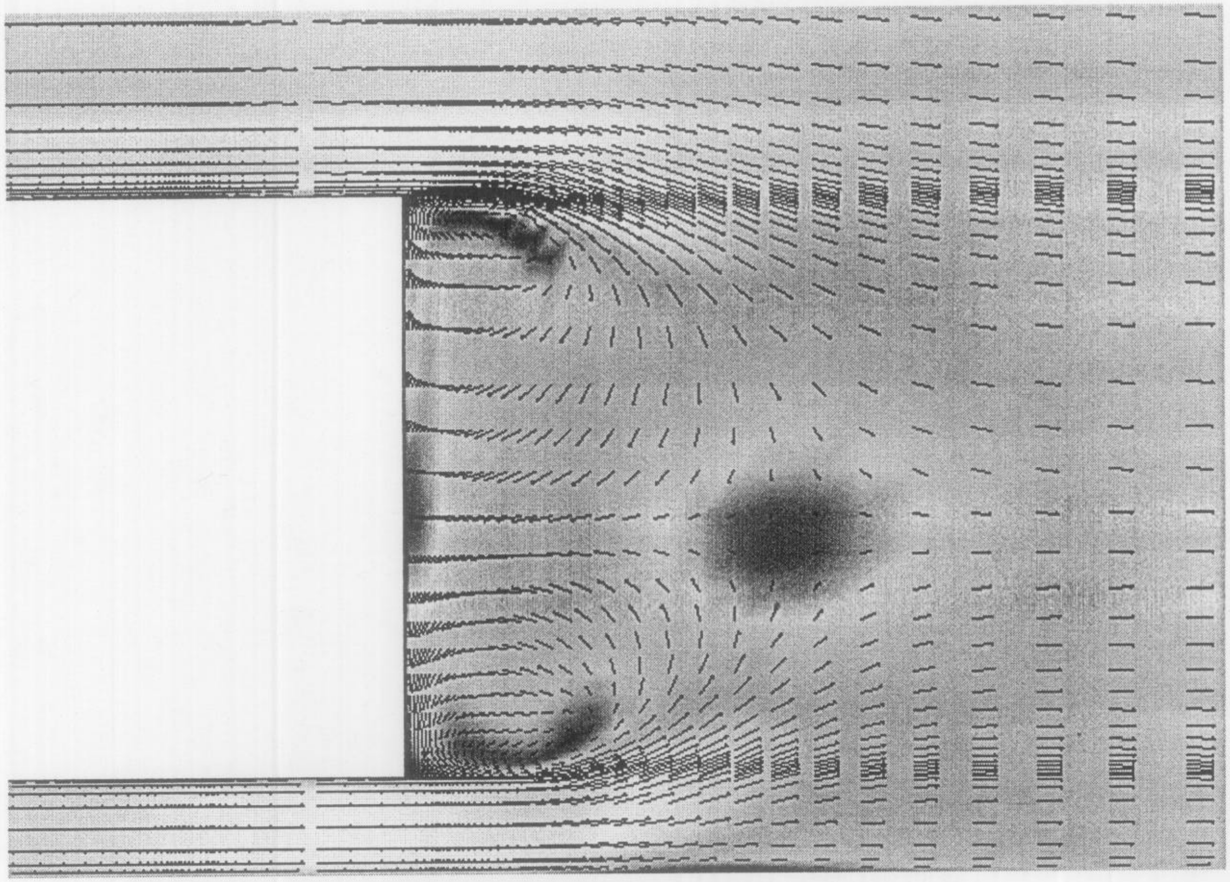
# Pressure Field Near Truck

- **Significant pressure drop in recirculation region on back end**

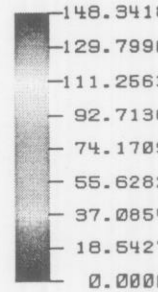



**Vertical Cut Plane** **Horizontal Cut Plane**

# Detail of Rear Recirculation

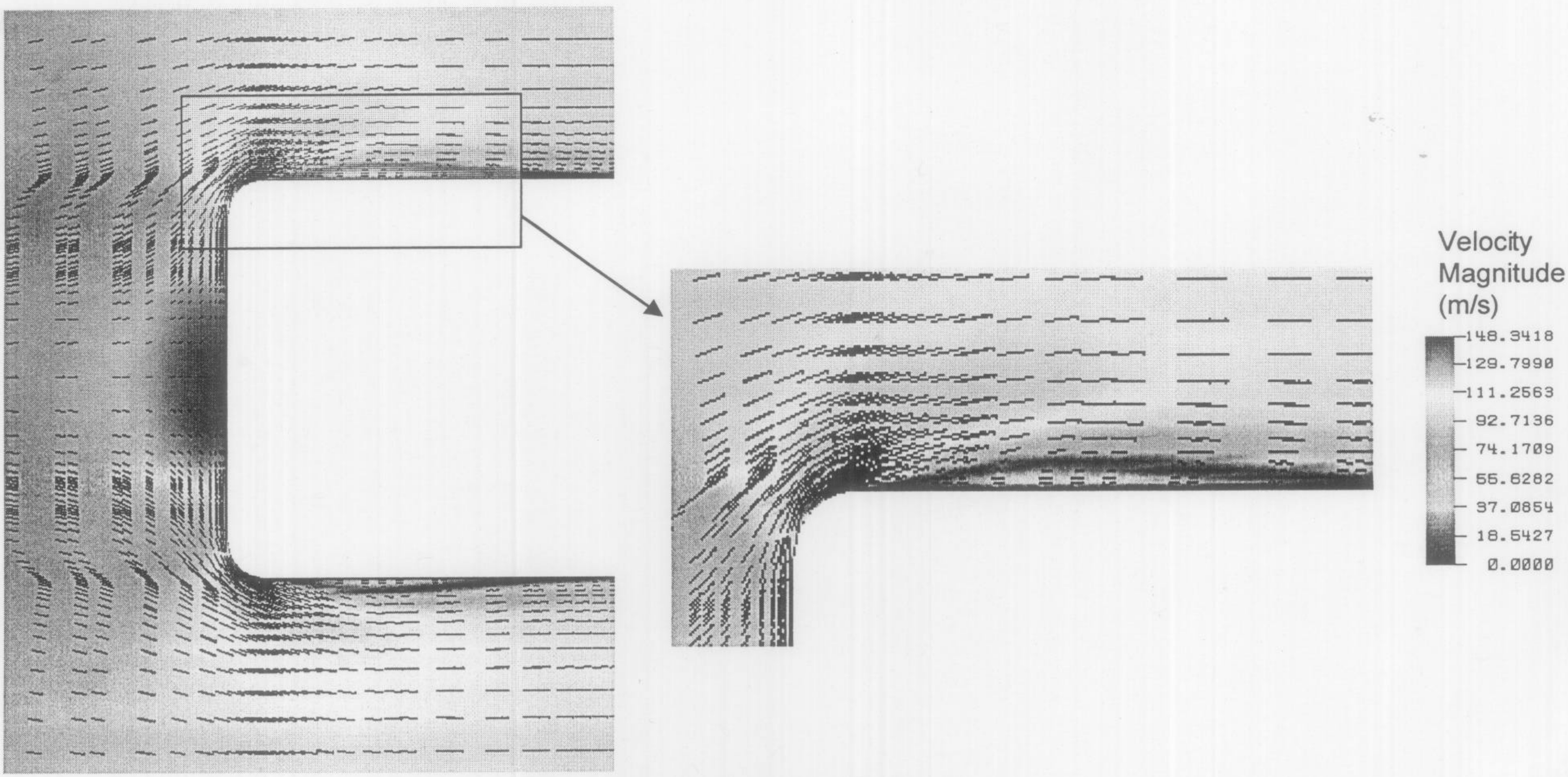


Velocity Magnitude (m/s)




**Vertical Cut Plane**

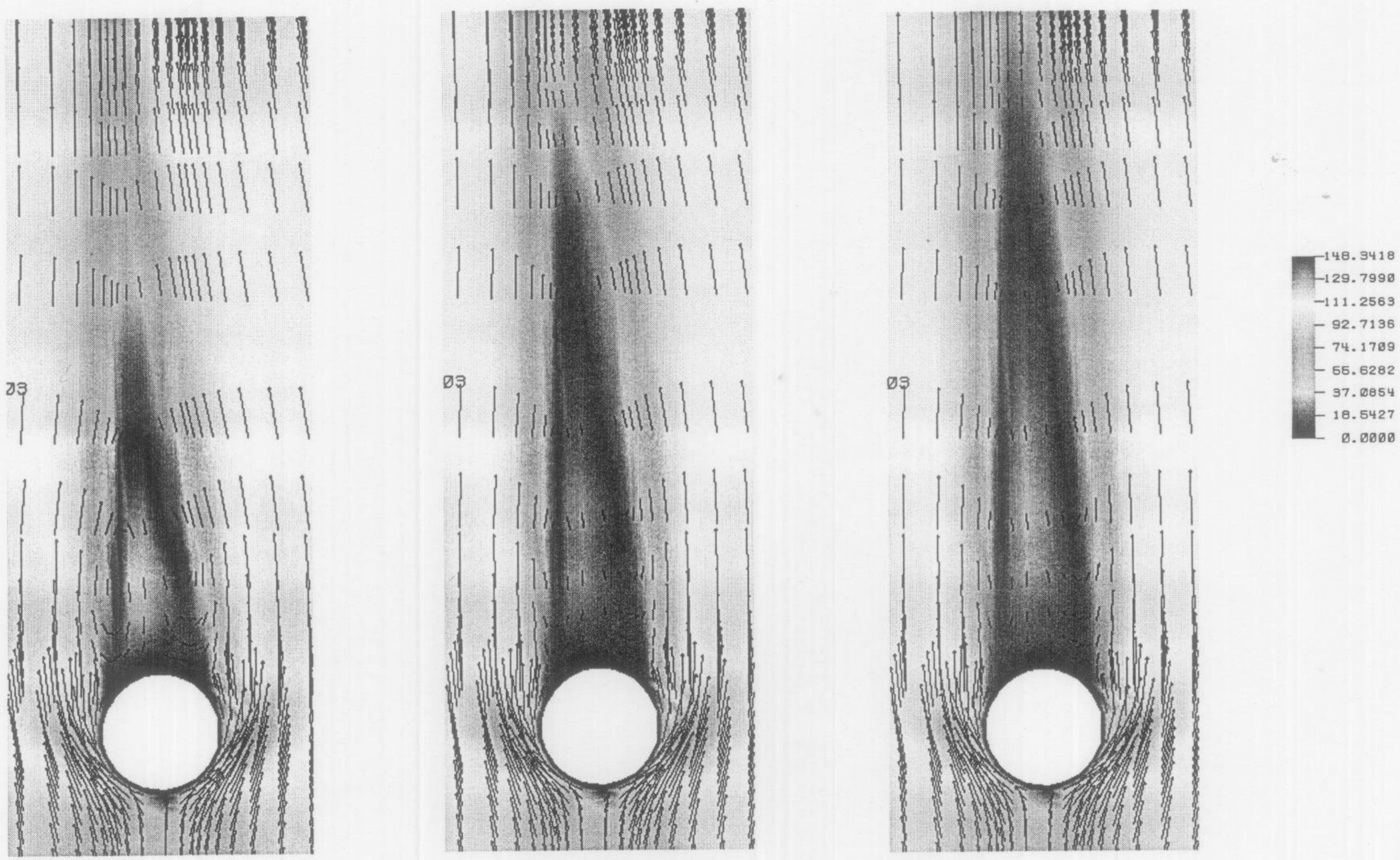
# Detail of Front End Separation



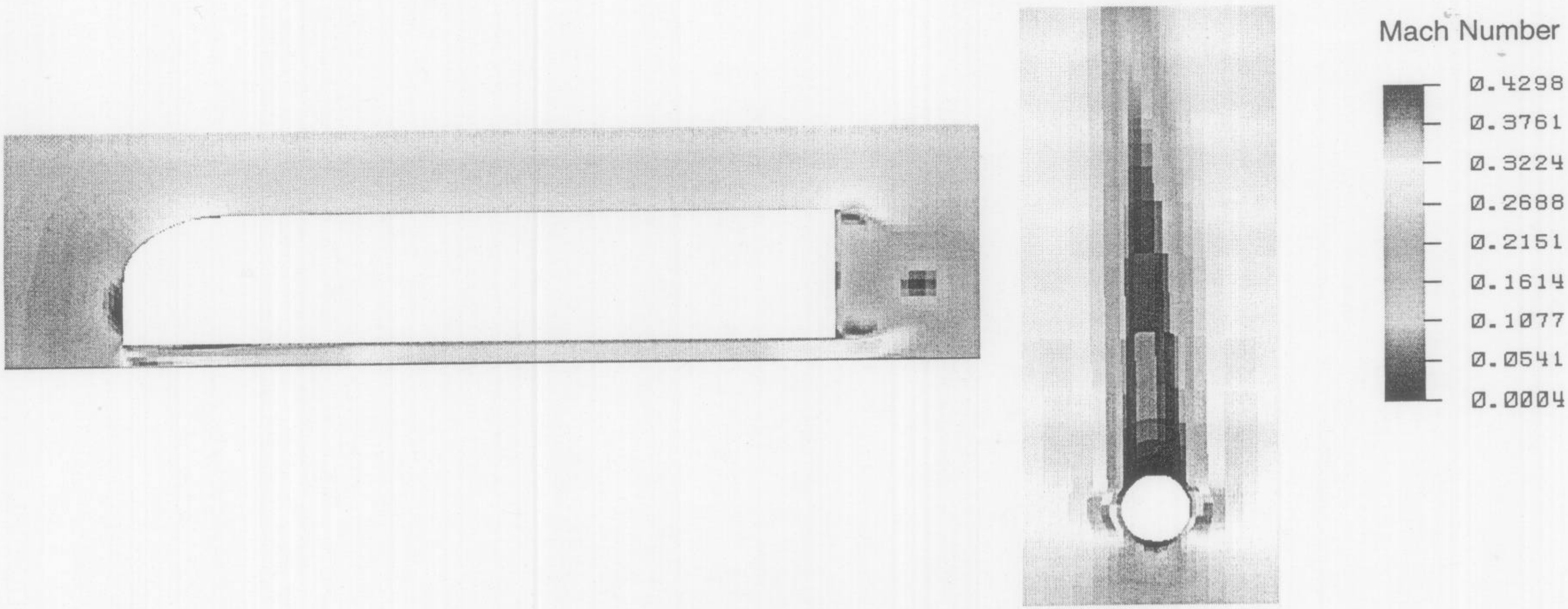

## Horizontal Cut Plane

8/16/99

# Post Velocity Field



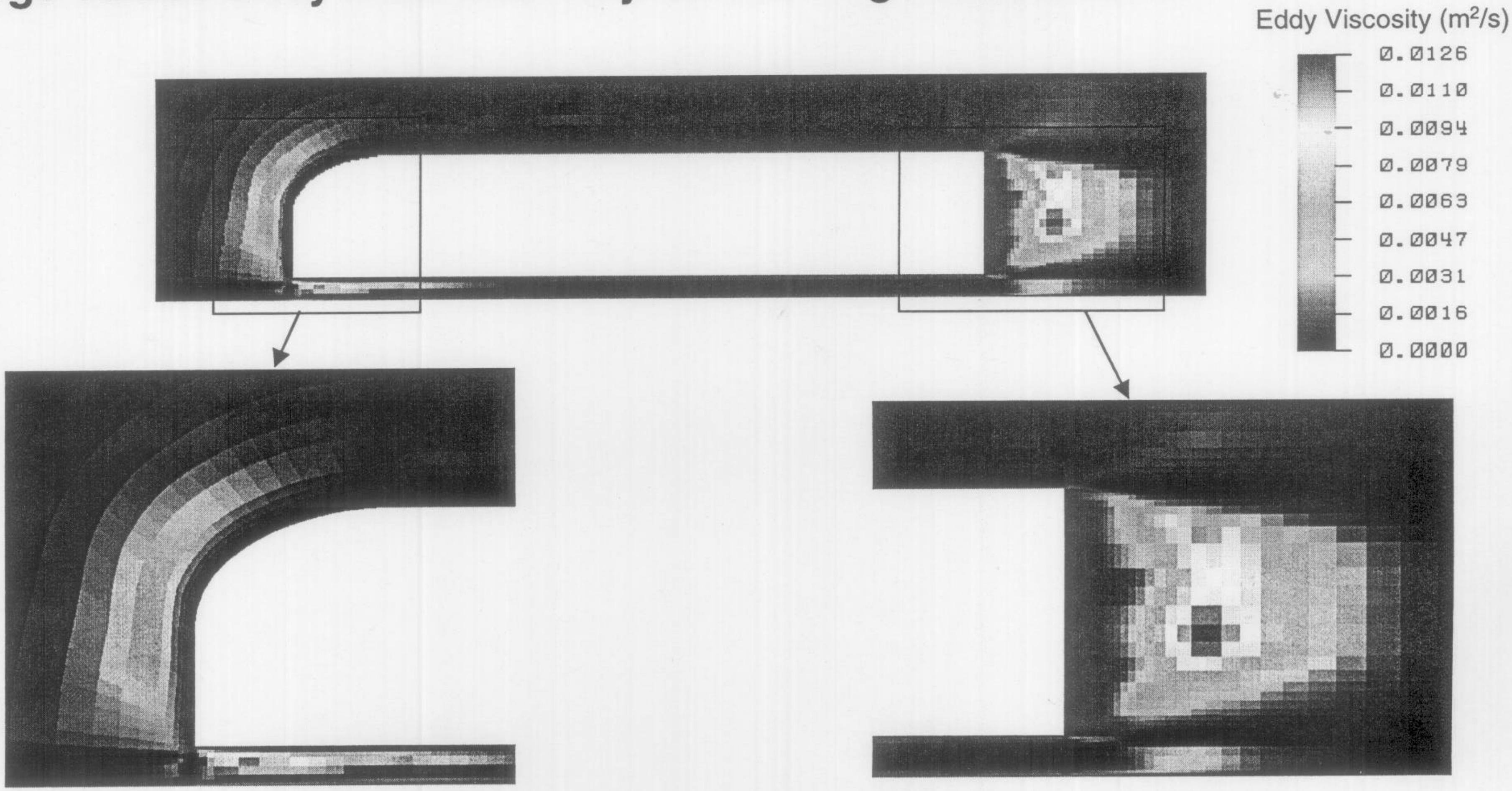
# Mach Number



Mach Number
0.4298
0.3761
0.3224
0.2688
0.2151
0.1614
0.1077
0.0541
0.0004

# Eddy Viscosity

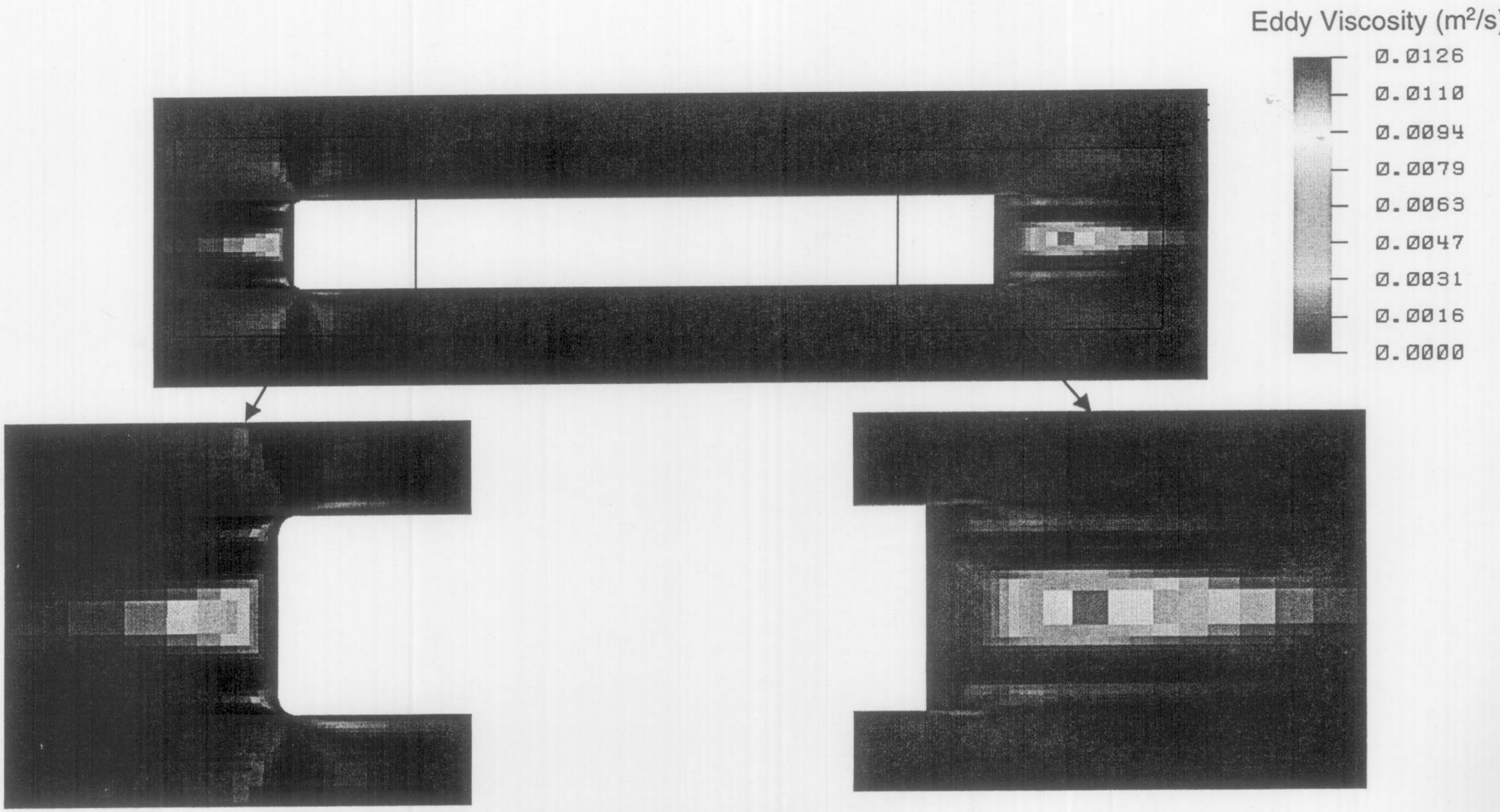
- Near wall eddy viscosity 50-100 times molecular viscosity
- Large values away from wall may be due to grid resolution




8/16/99

Vertical Cut Plane

# Eddy Viscosity




8/16/99

**Horizontal Cut Plane**

# Summary

- Compressible flow ALE3D with SGS model is currently being used to simulate Ma=0.27 NASA wind tunnel experiments
- Coarse 900,000 element unstructured mesh of NASA geometry generated
- Courant number time step constraints limit wall resolution
- Preliminary results show separation and vortex shedding phenomena
- Simulation has not run long enough to establish asymmetric flow patterns
- Predicted eddy viscosity at wall 50-100 times larger than molecular viscosity

# Future Plans

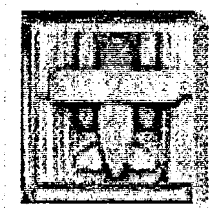
- Continue to run current geometry
  - Determine if solution has proceeded sufficiently beyond startup effects
- Develop next generation mesh
  - Correct the truck front end geometry
  - Further take advantage of unstructured mesh to eliminate elements away form truck surface and improve capturing of rounded surfaces
  - Better resolve the boundary layer
  - Study effect of further mesh refinement
- Develop results comparable to experimental data
  - Point statistics
  - Time averages

# Aerodynamic Design of Heavy Vehicles

- GOAL

  Develop and demonstrate the capacity to simulate and analyze aerodynamic flow around heavy truck vehicles using advanced computational tools.

- At GALCIT:



*"Computation of 3-D Unsteady Wake Flows Using Vortex Methods."*

<u>Technique</u>: Lagrangian Vortex Methods coupled with Panel Methods.

**Prof. Anthony Leonard, M. Brady (Post-Doc), L. Barba, M. Rubel.**

# 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

EPFL - Ecole Polytechnique Fédérale de Lausanne
P. Monkewitz, M. DeVille



# Numerical Simulation of the Flow around a Formula 1 Racing Car

*Mark L. Sawley, EPFL – DGM – Fluid Mechanics Laboratory*
*Roland Richter – Cray Research, Silicon Graphics Inc., Gland*

RANS

$\frac{1}{4} \times 10^6$ nodes
$10^6$ grid vol.

6 processors in SGI Origin 2000

RNG k-ε model.

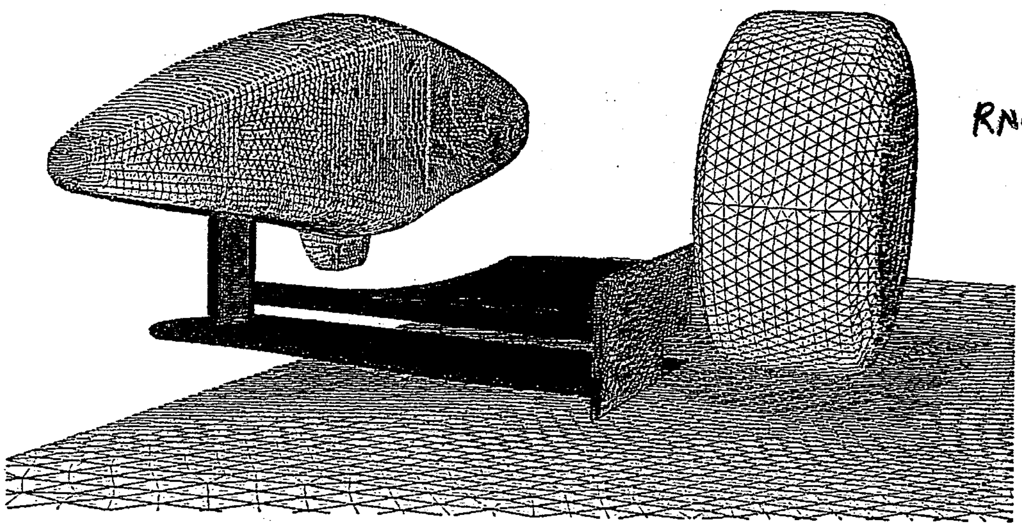


Fig. 2 – Surface mesh on half of the front-end configuration

Computational Fluid Dynamics plays an increasing role in the design process for the automotive industry, in particular for the prediction of aerodynamic characteristics. The present study is concerned with the simulation of the aerodynamic flow around the front section of a Formula 1 racing car. The numerical simulation involved four phases: geometry modelling, generation of the computational mesh, flow computation, and visualization and analysis of the flow solutions. Due to the significant resources required, the flow computation was performed on a high-performance parallel computer system, the Silicon Graphics Origin2000. Comparison of the numerical predictions with windtunnel data shows that the correct dependencies of the aerodynamic forces on various tuning parameters are obtained. Thus, despite the complexity of both the car geometry and the flow behaviour, the present study has shown that numerical simulation can provide a wealth of information useful to the design process.

coupled, indeed it is the overall aerodynamic behaviour of the vehicle that governs its performance.

The aerodynamic forces exerted on a Formula 1 racing car can be modified by tuning various properties of the car and its appendages. The major goal is to provide maximum downforce to facilitate power transfer from the engine, and to enhance stability especially when cornering. Nevertheless, due to the coupling of the flow around different areas of the car, certain appendages may be required to fulfil multiple aerodynamic functions. For example, the front wing both provides downforce and conditions the flow through the underbody, diffuser and radiator air intakes. In order to optimize the performance of the car, it is important to determine how the aerodynamic forces vary with the tuning of various parameters such as road height, wing configuration and flap angles.

Traditionally, the aerodynamic optimization of racing cars has relied entirely on designer experience and racetrack testing. Since a number of years, windtunnel testing has also become an integral part of the design process, especially for advanced racing such as Formula 1. Windtunnel testing can provide a systematic study of various tuning options within a controlled environment. It is, however, generally restricted to provide global measurements of the aerodynamic forces exerted on the car. Sauber Petronas Engineering AG undertakes approximately 33 weeks of windtunnel testing

Hermann Föttinger Institute (H. Fernholz).

### 2.1.4 Wandnahe Messung der Turbulenzstruktur in inkompressiblen Wandstrahlen mit und ohne Gegenstrom in der Außenströmung

Bearbeiter: M. Schober, F. Grewe
Forschungsträger: DFG, TUB

Wandstrahlen werden z.B. bei der Auftriebserhöhung von Tragflächen und zur Kühlung von Turbinenschaufeln angewendet. Im ersten Fall ist es erwünscht, daß der Wandstrahl möglichst rasch seine Energie in die sich sonst ablösende Grenzschicht abgibt. Im zweiten Fall ist es jedoch das Ziel, die Durchmischung mit der Außenströmung zu verhindern, um die kühlende Schicht des Wandstrahles so lange wie möglich zu erhalten. Diese beiden gegensätzlichen Forderungen können durch die Manipulation der am Wandstrahlaustritt abgehenden Scherschicht durch einen dünnen Zylinder (Draht) erfüllt werden.

no trip wire

taut trip wire

oscillating trip wire

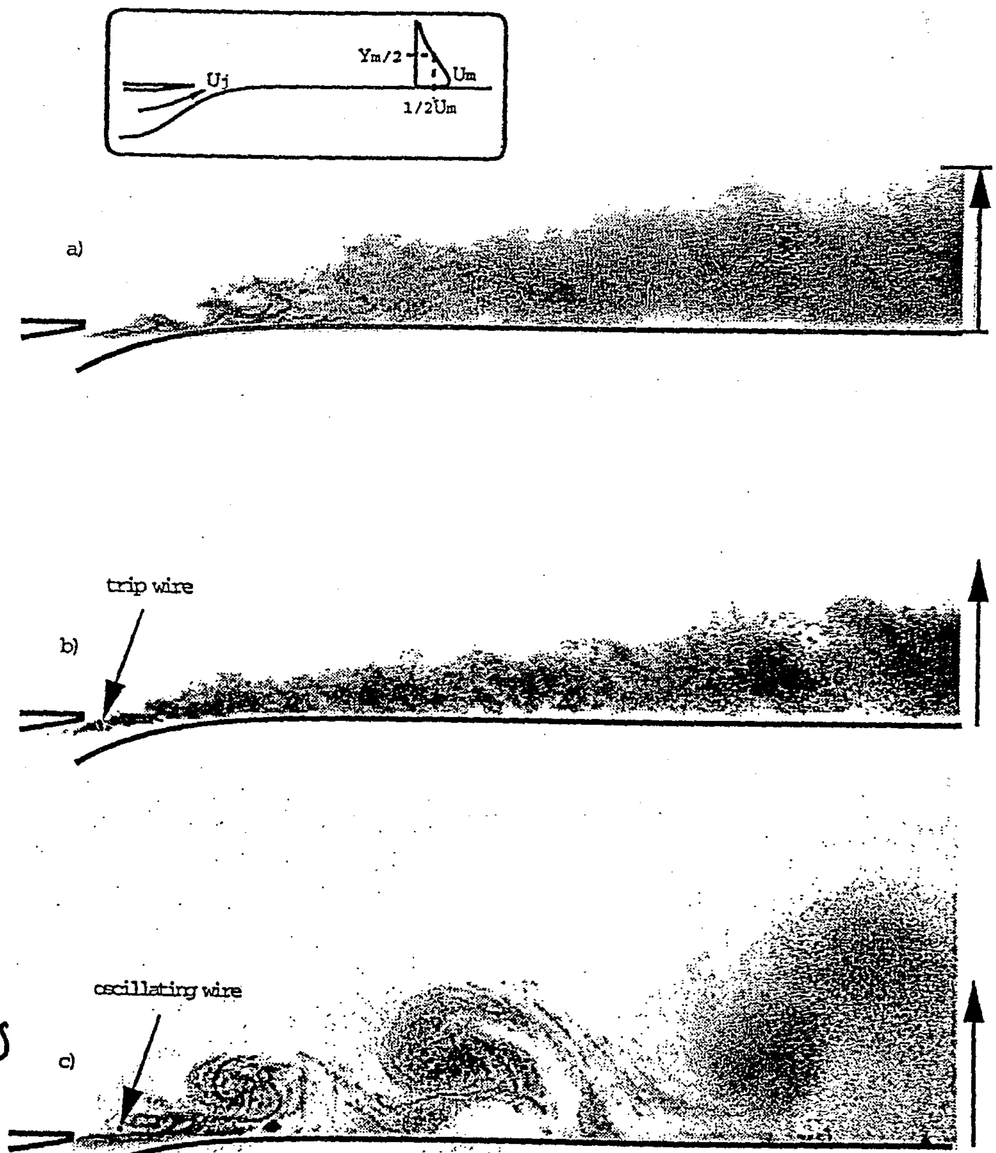



**Abbildung 11:** Scherschichtstrukturen am Wandstrahlaustritt ($Re_j = 5000$; $0 < x/b < 15$, $b = 8$ mm)
a) nichtmanipulierter Wandstrahl;
b) durch ruhenden Stördraht manipulierter Wandstrahl;
c) durch oszillierenden Stördraht manipulierter Wandstrahl.

Advanced Subgrid Models for LES

# A TENSOR-DIFFUSIVITY SUBGRID MODEL FOR LARGE-EDDY SIMULATION

A. LEONARD *
*Graduate Aeronautical Laboratories, California Institute of Technology, USA*

G. S. WINCKELMANS
*Center for Systems Engineering and Applied Mechanics, Université catholique de Louvain, Belgium*

Abstract. Subgrid-scale models for large-eddy simulation that are based on exact series expansions for filtered products are considered. In particular, if the first two terms are retained, the result is a diffusive subgrid term with a tensor diffusivity. This tensor is proportional to the rate-of-strain tensor of the large-scale velocity field. This leads to negative diffusion in the stretching directions. Implications of this result are considered for the filtered scalar advection-diffusion equation and for the momentum equation for incompressible fluid flow. When coupled with a dynamic Smagorinsky term to form a mixed model, very encouraging results are shown for turbulent, isotropic decay and for turbulent channel flow. In addition, it is shown that the model, mixed or not, transforms appropriately when differing frames of reference are considered. Modifications to the model are suggested for the case in which the unfiltered field(s) has discontinuities.

## 1. Introduction

In most formulations of large-eddy simulation one is faced with the task of modeling filtered product terms such as in the one-dimensional example:

$$\overline{uv}(x) = \int_{-\infty}^{\infty} \overline{G}\left(\frac{x-x'}{\sigma}\right) u(x')\, v(x')\, \frac{dx'}{\sigma}\,. \tag{1}$$

Here $\overline{G}$ is the filter function and $\sigma$ is the characteristic filter width. Such products appear in the evolution equations for $\overline{u}$ and $\overline{v}$ so that $\overline{u}(x,t')$ and $\overline{v}(x,t')$ for all $t' \leq t$ is available for such a model. Consider the gaussian

* On leave: University of Cambridge, Isaac Newton Institute for Mathematical Sciences, 20 Clarkson Road, Cambridge CB3 0EH, United Kingdom

filter,

$$\overline{G}(z) = \frac{1}{\sqrt{\pi}} \exp(-z^2) \,. \tag{2}$$

We then have the result (Bedford & Yeo, 1993; Leonard, 1997)

$$\boxed{\overline{uv} = \sum_{k=0}^{\infty} \left(\frac{\sigma^2}{2}\right)^k \frac{1}{k!} \frac{\partial^k \overline{u}}{\partial x^k} \frac{\partial^k \overline{v}}{\partial x^k} \,.} \tag{3}$$

The full infinite series above is equivalent to deconvolving $\overline{u}$ and $\overline{v}$ (clearly a singular operation) then forming the product $uv$ and then applying the filter operation. In this paper we focus on sub-grid models that use as their basis the first two terms in the above expansion. For $d$ dimensions we have

$$\boxed{\overline{uv} \approx \overline{u}\,\overline{v} + \frac{\sigma^2}{2} \frac{\partial \overline{u}}{\partial x_\ell} \frac{\partial \overline{v}}{\partial x_\ell}} \tag{4}$$

where repeated indices are summed and $\ell = 1, 2, .., d$. See (Carati et al, 1998) and a companion paper in this volume by Carati *et al.* for the extension of this result to other filters.

This model was proposed some time ago (Leonard, 1974; Clark et al, 1979) as an approximation to the subgrid stress due to the interaction between the resolved scales and the resolved scales plus the subgrid scales. Clark *et al.*(1979) combine it with a Smagorinsky model and subject the resulting mixed model to *a priori* tests on decaying isotropic turbulence. Since then a number of studies (e.g. (Liu et al, 1994; Borue & Orszag, 1998)) have noted the high correlation between the tensor diffusivity stresses and the actual subgrid stresses in *a priori* tests as did Clark *et al.*. Recently Vreman *et al.*(1996) had good success in a LES of the evolution of a turbulent mixing layer by coupling this model with a dynamic Smagorinsky model. This approach to subgrid modeling is related to the more general approach in which an attempt is made to recover directly some of the information that has been lost due to filtering (Bardina et al, 1983; Shah & Ferziger, 1995; Borue & Orszag, 1998; Domaradski & Saiki, 1997; Stolz & Adams, 1999).

## 2. Application to the filtered advection-diffusion equation

with P. Moeleker ASCI supported

Application of (4) to the scalar advection-diffusion equation for the filtered scalar field $\overline{\psi}$ gives the result (Leonard, 1997)

$$\frac{\partial\overline{\psi}}{\partial t}+\overline{\mathbf{u}}\cdot\nabla\overline{\psi}=-\frac{\sigma^2}{2}\overline{S}_{ij}\frac{\partial^2\overline{\psi}}{\partial x_i\partial x_j}+\kappa\,\nabla^2\,\overline{\psi} \tag{5}$$

where $\overline{S}_{ij}$ is the strain-rate tensor of the filtered incompressible velocity field,

$$\overline{S}_{ij}=\frac{1}{2}\left(\frac{\partial\overline{u}_i}{\partial x_j}+\frac{\partial\overline{u}_j}{\partial x_i}\right)\,. \tag{6}$$

Thus $\overline{S}_{ij}$ plays the role of a diffusion tensor for the filtered scalar field. Apparently (5) is now a closed evolution equation, giving the solution of $\overline{\psi}$ for the case of smooth velocity fields, and for small molecular diffusivities $\kappa$ we can neglect the second term on the RHS of (5). This is a nontrivial result given that even smooth velocity fields yield chaotic particle motions.

However, there is a price to pay. The diffusion operator is ill-conditioned as can be seen as follows. Transforming to principal coordinates of $\overline{S}_{ij}$, $\mathbf{x}'$, we find that the first term on the RHS of (5) for three-dimensional transport becomes

$$-\frac{\sigma^2}{2}\overline{S}_{ij}\frac{\partial^2\overline{\psi}}{\partial x_i\partial x_j}=-\frac{\sigma^2}{2}\left(\overline{\alpha}\frac{\partial^2\overline{\psi}}{\partial x_1'^2}+\overline{\beta}\frac{\partial^2\overline{\psi}}{\partial x_2'^2}+\overline{\gamma}\frac{\partial^2\overline{\psi}}{\partial x_3'^2}\right) \tag{7}$$

where the eigenvalues of $\overline{S}_{ij}$, $(\overline{\alpha},\overline{\beta},\overline{\gamma})$ satisfy

$$\overline{\alpha}\geq\overline{\beta}\geq\overline{\gamma}\qquad\qquad\overline{\alpha}+\overline{\beta}+\overline{\gamma}=0 \tag{8}$$

so that along the stretching direction(s), $x_1'$ (and possibly $x_2'$) we have effectively negative diffusion. This corresponds to local directional backscatter. Thus to use the above tensor diffusivity it appears that one must regularize the method in a meaningful way.

One possibility is to use a numerical technique that maintains control over the high frequency content of the solution. We have found that representing $\overline{\psi}$ as a collection of lagrangian particles, each of which has an anisotropic gaussian distribution, gives us the desired control over the high

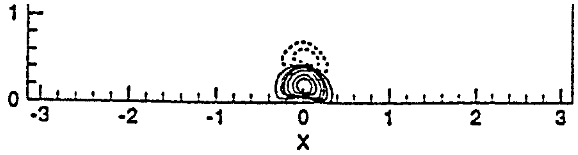
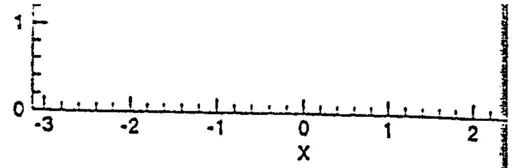



*Figure 1.* Advection-diffusion of a filtered scalar according to (5): (a) finite diff method (b) lagrangian particle method.

is gaussian. At the time shown, the finite-difference solution is seen blowing up. Use of a Fourier spectral method gives a qualitatively si blowup. The accuracy of the particle method has been verified by a resolution computation of the unfiltered equation.

## 3. Application to LES of turbulent, isotropic decay

Use of the model (4) on the filtered, constant density, incompressible mentum equation yields

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial}{\partial x_j}(\overline{u}_i\overline{u}_j) = -\frac{\sigma^2}{2}\,\overline{S}_{j\ell}\,\frac{\partial^2 \overline{u}_i}{\partial x_j \partial x_\ell} - \frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + \nu\,\nabla^2\,\overline{u}_i\,.$$

+ dynamic Smagorinsky

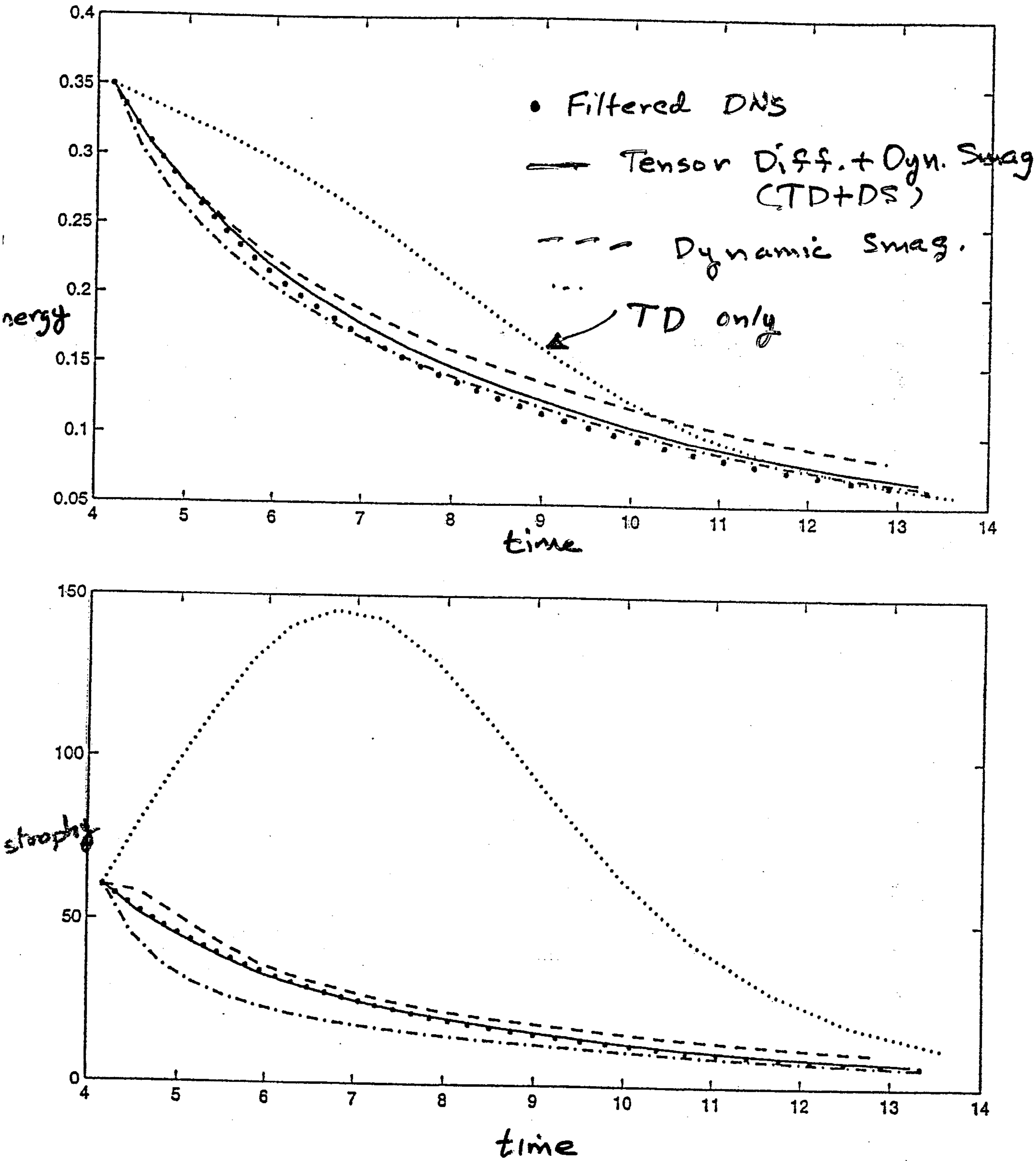
We believe the model term (first term on the RHS above) to be an impo component of a subgrid model, e.g., in homogeneous turbulence, the e loss rate, $< \epsilon^M >$, of the large eddies due to this term is

$$< \epsilon^M >= I = \frac{\sigma^2}{2} < \overline{u}_i \frac{\partial}{\partial x_j}\left(\frac{\partial \overline{u}_i}{\partial x_\ell}\frac{\partial \overline{u}_j}{\partial x_\ell}\right) >$$

which, for isotropic decay, can also be written as

$$I = -\frac{\sigma^2}{2} < \overline{S}_{ij}\,\frac{\partial \overline{u}_i}{\partial x_\ell}\frac{\partial \overline{u}_j}{\partial x_\ell} > .$$

Thus, $-I$ is proportional to the skewness of the large scale velocity de ives. As the skewness is negative in turbulence, the tensor diffusivity n




ure 2. Resolved energy, $E(t)$, and enstrophy, $\mathcal{E}(t)$: truncated DNS (solid circle); sor diffusivity (dot); tensor diffusivity + dynamic Smagorinsky (solid); dynamic agorinsky (dash); dynamic Smagorinsky with sharp cutoff (chained-dot)

odel: 2.887 versus 4.112.

homogeneous directions (applied in wave-space) and top hat in the non-homogeneous direction:

$$\overline{\mathcal{G}} = \exp\left(-k_x^2\Delta_x^2/6\right)\ \frac{\sin\left(k_y\Delta_y\right)}{\left(k_y\Delta_y\right)}\ \exp\left(-k_z^2\Delta_z^2/6\right) . \qquad (20)$$

TURBULENT CHANNEL FLOW

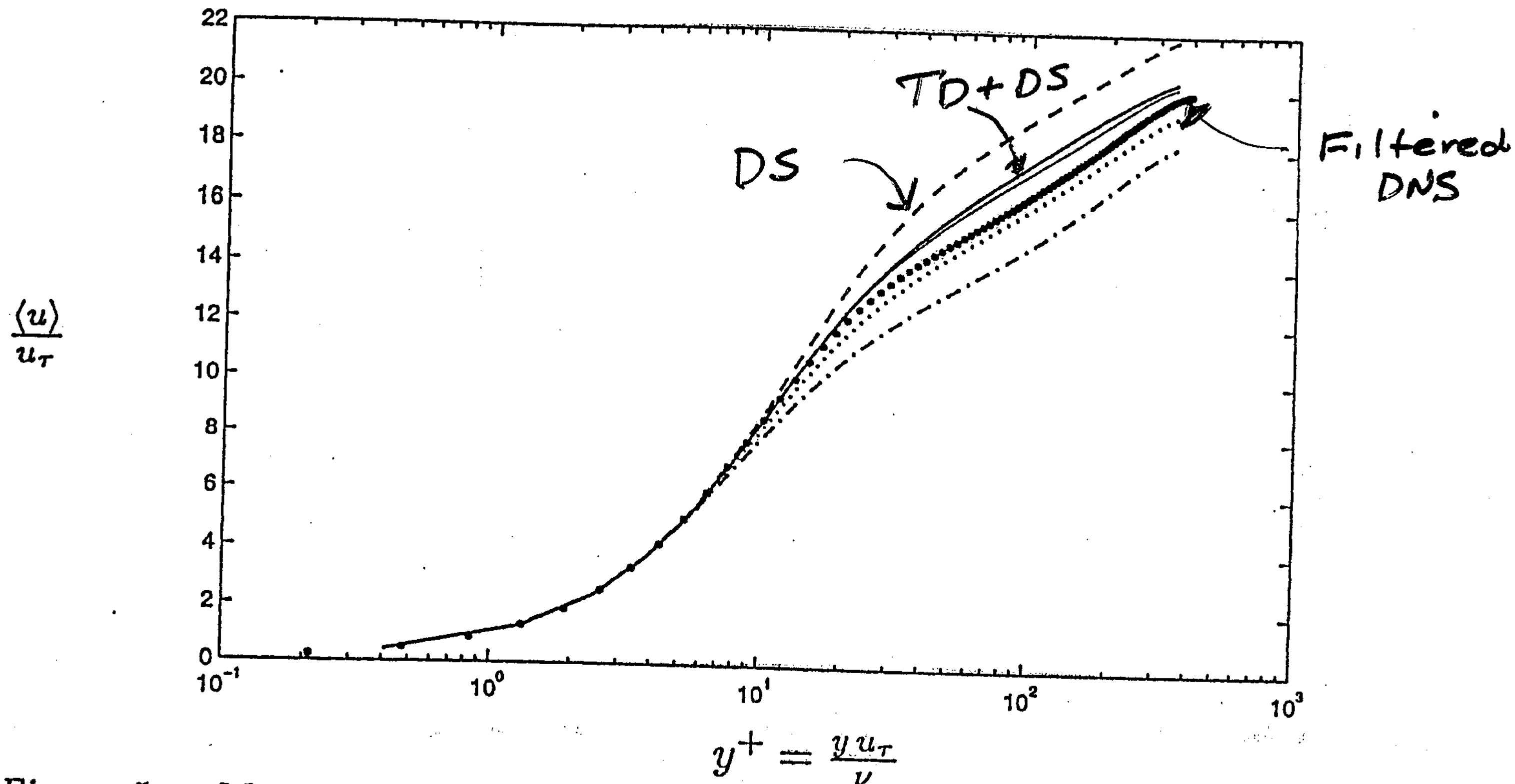



*Figure 5.* Mean velocity profiles: DNS (solid circle), tensor diffusivity + dynamic Smagorinsky, F1 (solid) and F2 (thin solid); dynamic Smagorinsky, F1 (dash); dynamic Smagorinsky, $x$-$z$ sharp cutoff (dot), no model (chained-dot)

Results on normalized mean profiles as a function of normalized distance to the wall are provided in Figs. 5 and 6: velocity, model stress and model dissipation. With the ...

# Panel Methods

1

- Geometry Definition and Panel Generation

2

- Induced Velocity (Matrix) Calculation

3

- Solution of System of Linear Eqns. For Singularity Distribution

4

- Calculation of Flow Field Parameters

# Advanced Concepts in the Panel Code

1. Geometry Definition: Two approaches,

- Unstructured surface mesh: advancing front method (M. Brady).
  - High order
  - Adaptive capabilities
  - As yet, no capacity for CAD interfacing
- NASA's GridTool and VGRID technology.
  - GridTool features CAD file support, including IGES.
  - VGRID uses advancing front method to generate unstructured meshes.
  - Part of NASA's TetrUSS system, 1996 NASA Software of the Year Award.

# Advanced Concepts in the Panel Code (cont.)

2. Induced Velocity Calculation:
   - Fast summation algorithms (multipole expansion)… O(N) operations permit increased number of panels.
   - No need to build and store an $N$ x $N$ matrix.

3. Solution for Unknown Singularities:
   - Modern iterative schemes: fast convergence.

# Hybrid Vortex Panel-particle Method

Panel Code

Potential flow calculation:

Velocity at each survey point

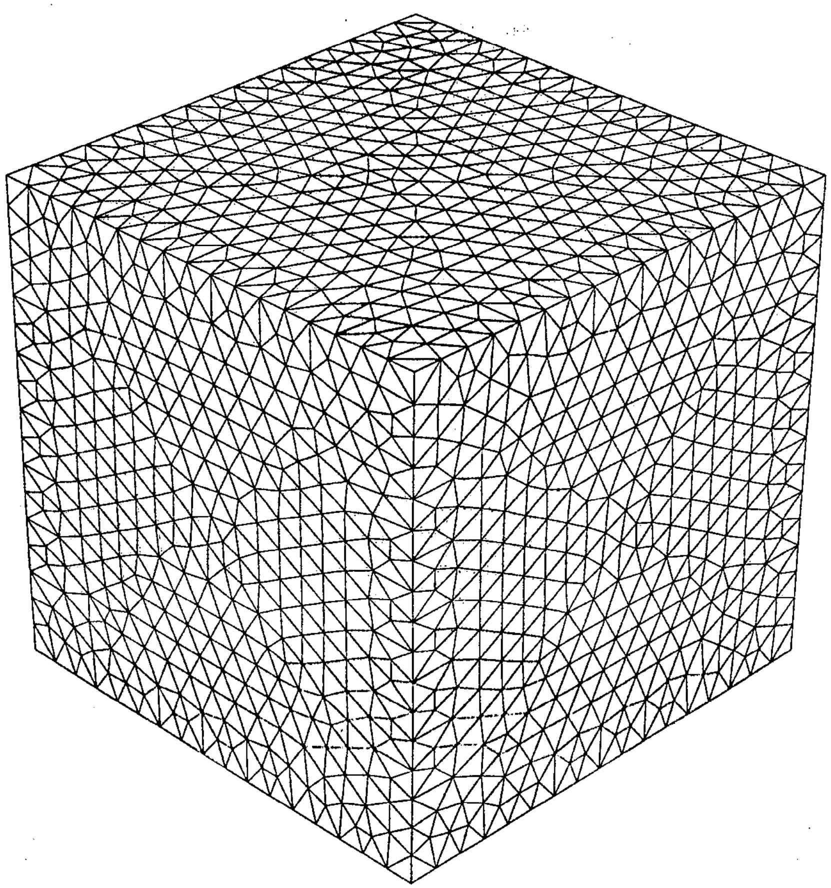
New free-stream conditions

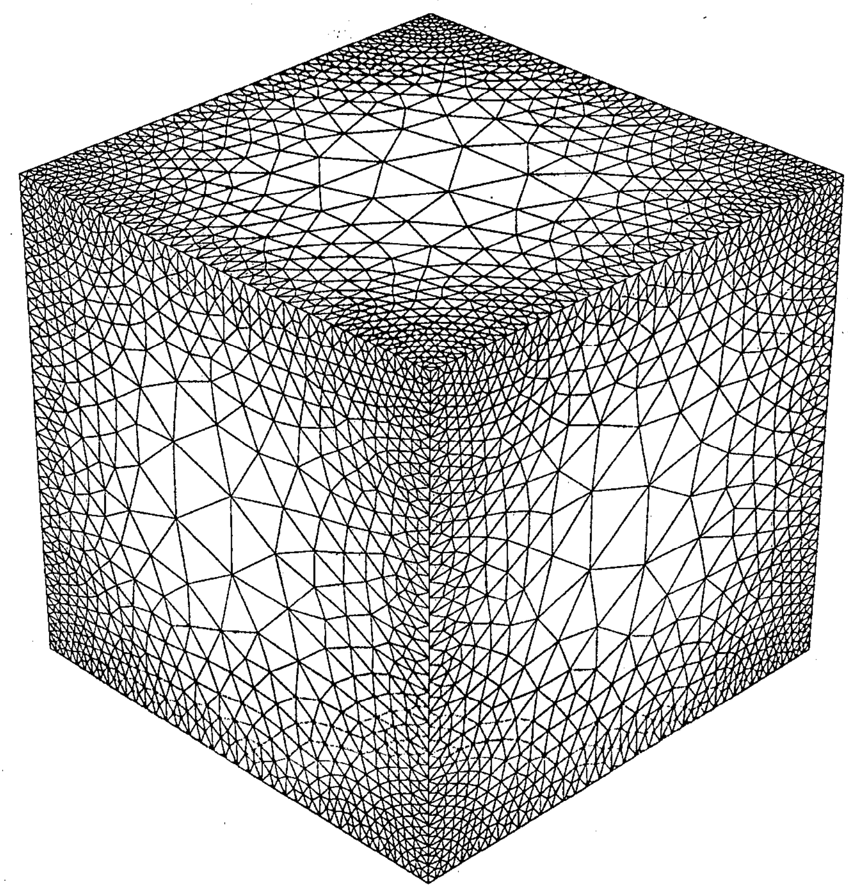
One time step

Translate to vorticity: Shedding model.

Convect and diffuse wake vortices

# Advanced Panel Method





# Advanced Panel Method