

# Combining Experimental Data, CFD, and 6-DOF Simulation to Develop a Guidance Actuator for a Supersonic Projectile



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| Report Documentation Page                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                                    |                                     |                                            | Form Approved<br>OMB No. 0704-0188          |                                    |
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# Outline

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- Why guided bullets?
- Initial Results
- Wind tunnel results
- CFD
- Subscale Range Tests
- Comparison with CFD and Reconciliation
- Full Scale Range Tests



# Swarmers Concept for Cruise Missile Defense

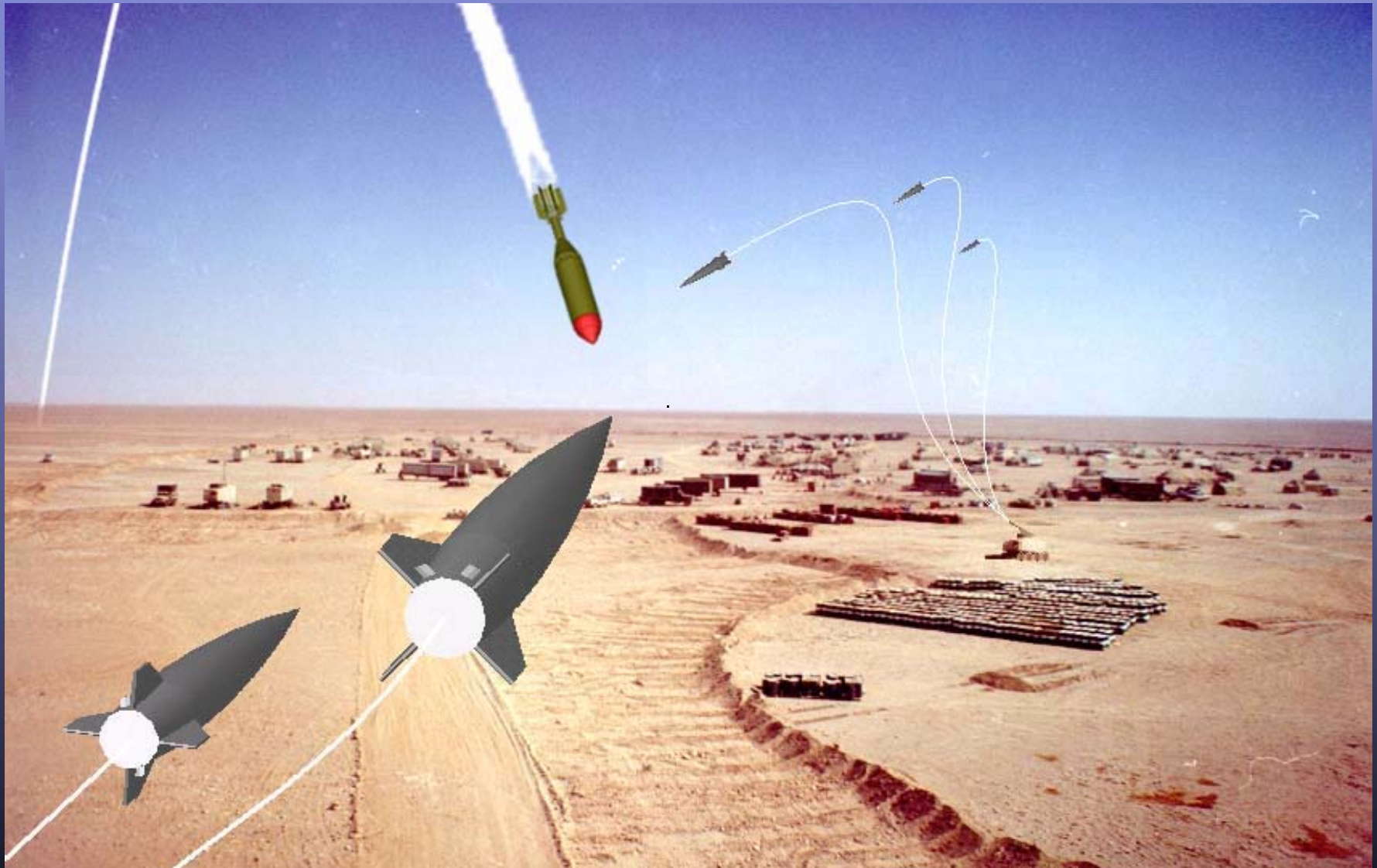


Goal: Defend against maneuvering cruise missiles.

Features:

1. High supersonic projectiles (Mach 4+)
2. High g maneuvers (50g)
3. Short Mission (4 sec)
4. Swarm of Projectiles

# Guided bullets to intercept mortars



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# GTRI Phase 1 Efforts

## Ball M33 Lab Tests

Optical Verification of changes in flow due to mass injection at

Nose



Midbody



Measurements of mass flow required to affect flow

Can Alter

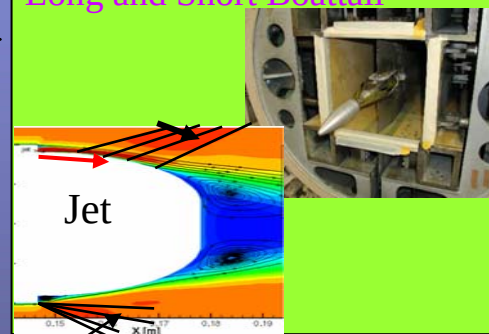


Flow

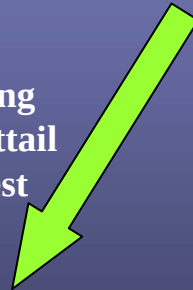
## 40mm Scaled Ball M33

USAFA Tunnel / CFD

Mass Injection : Nose,  
Midbody, Boattail  
Long and Short Boattail



Long  
Boattail  
Best



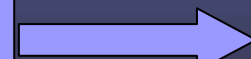
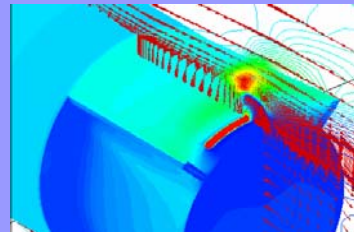
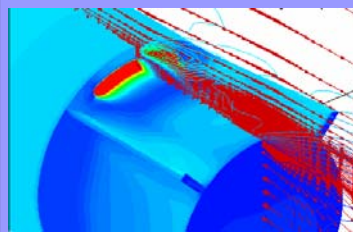
Aft Mass  
Injection  
Best



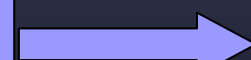
## 40mm ARL Projectile

U. Texas Tunnel / CFD – forces and moments

Aft Mass Injection : Tangential and Normal



Normal  
Mass Inject  
Better

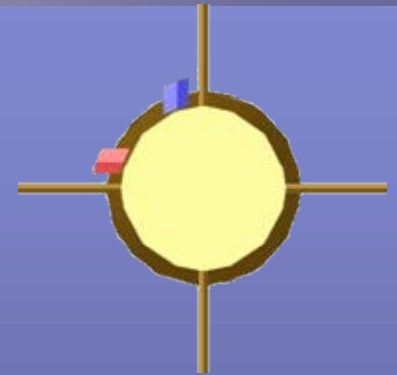
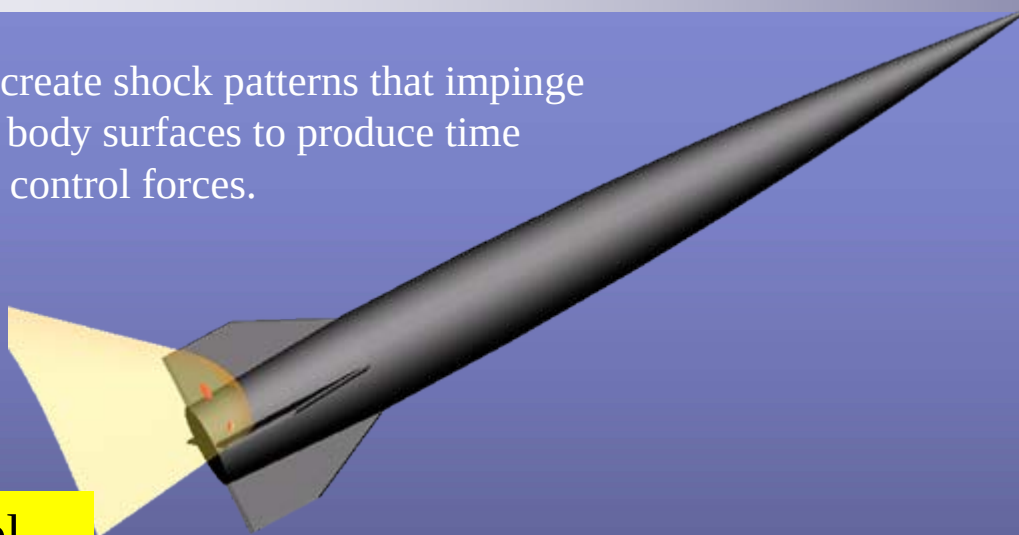


Projectile  
Unstable

# GTRI Second Year Efforts

# Concept of implementing flow control near fin

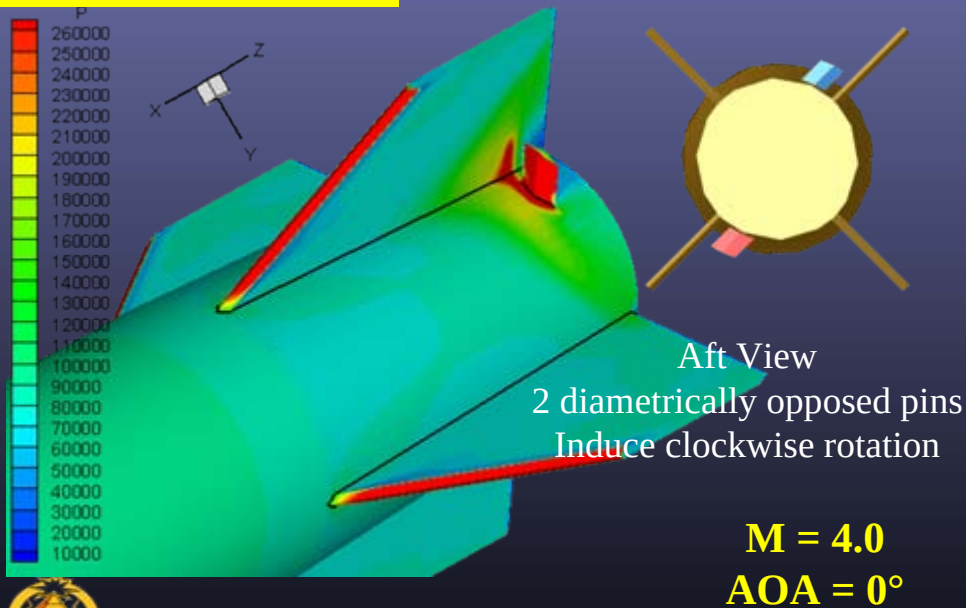
Actuators create shock patterns that impinge on fin and body surfaces to produce time dependent control forces.



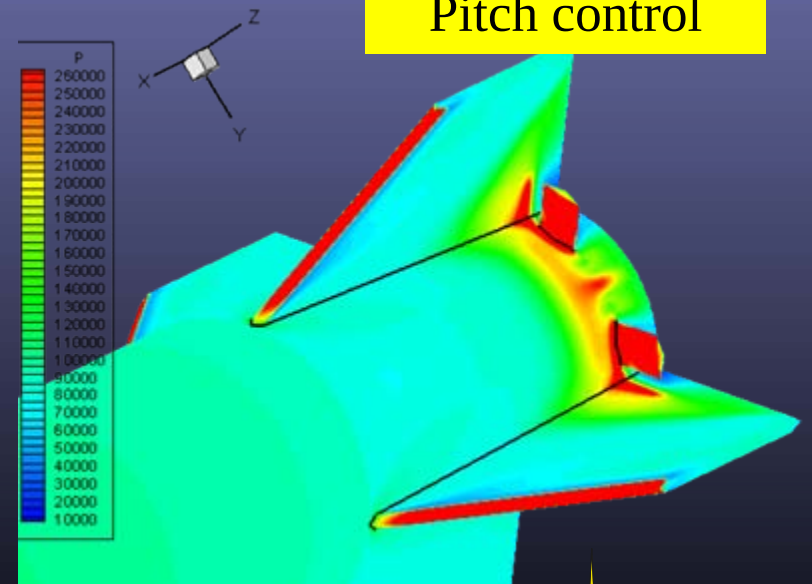
Aft View

2 pins close to adjacent fins  
Induce Angle of Attack Change

## Roll control



## Pitch control



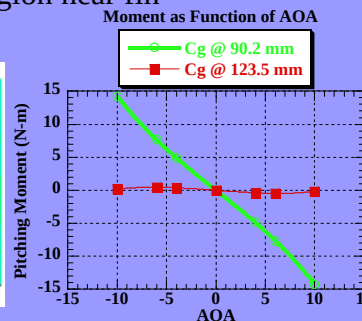
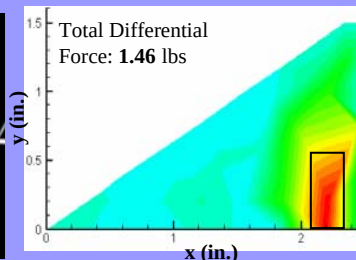
# GTRI

## Phase 2 Efforts

### Fin Interactions

GTRI Tunnel

Measured forces generated by pins and mass injection in region near fin



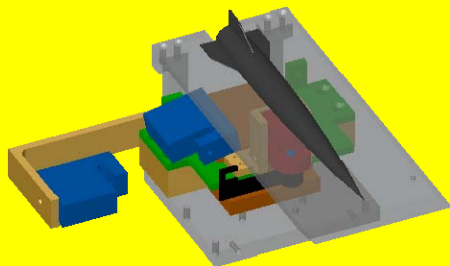
Pins Near Fins  
Generate  
Strong Turning  
Moment

Too Much  
Volume  
Required for  
Mass Injection

Input from  
ARL on  
Size, Shape,  
Mass Dist.

Need System Study to  
Define: Cg location  
Fin Shape/Size  
Roll or Fin Stabilized?  
Actuation Concept and  
Preliminary Design

½ Body Test Rig



3D Effects

Steering Force  
(Steady & Unsteady)

CFD

Understand Fluid  
Dynamic  
Interactions

Preliminary  
Actuators

Available  
Steering  
Force

Fire Round  
at ARL

Test Concept  
and Hardware



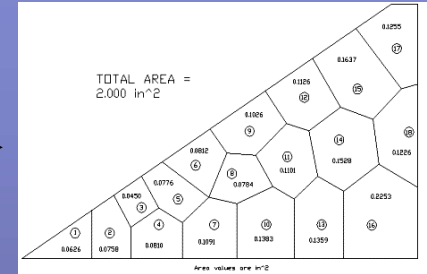
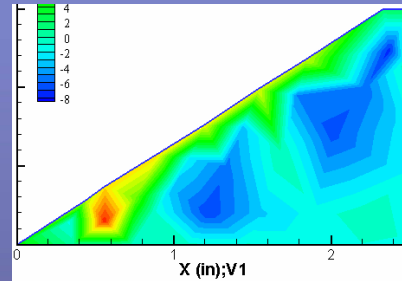


# Understanding Fin-Body Corner Flow Interactions

Flow over fin and cylinder



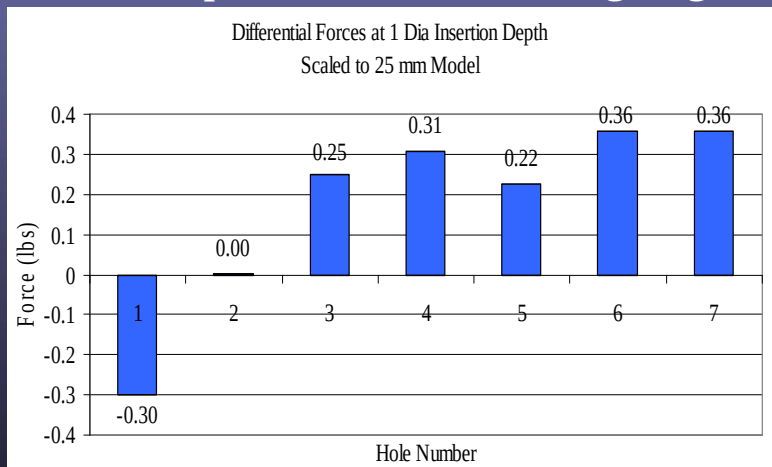
Creates pressure changes on fin



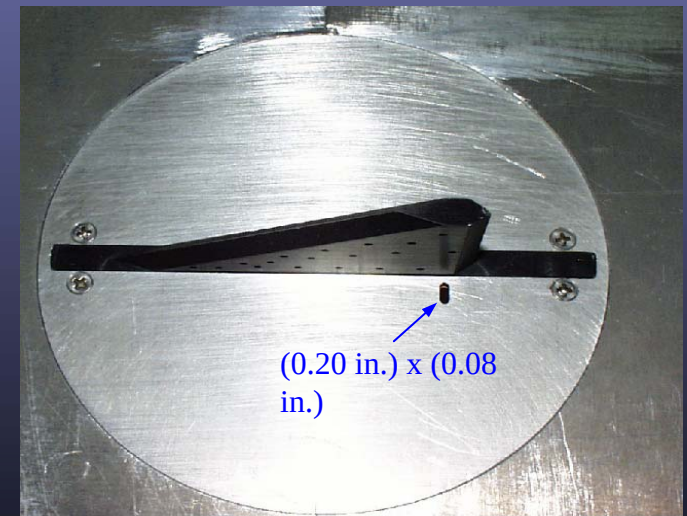
Pressures used to calculate force on fin

Early results proved two things:

1) More force produced near trailing edge of fin



2) Mass flow requirements for fluid injection too high



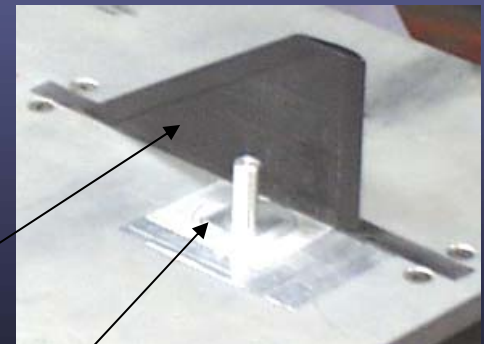
# Pin-Fin Interaction Parametric Study

- Goal: Understand trades of pin location and pin shape
- Rationale: Recognize likelihood of non-optimal pin placement and geometry
  - Data acquired at  $M = 1.7$
  - Data for 4 different pin geometries
    - Round pins 0.1 and 0.2 inch diameter
    - Flat pin with same frontal area as 0.2 round pin
    - Trapezoidal pin with same frontal area as 0.2 round pin
  - Pin height fixed at 0.5 in
  - Spacer blocks used to position pin



Experimental Setup

Rectangle 0.2      Round 0.2      Round 0.1      Trapezoid



Fin

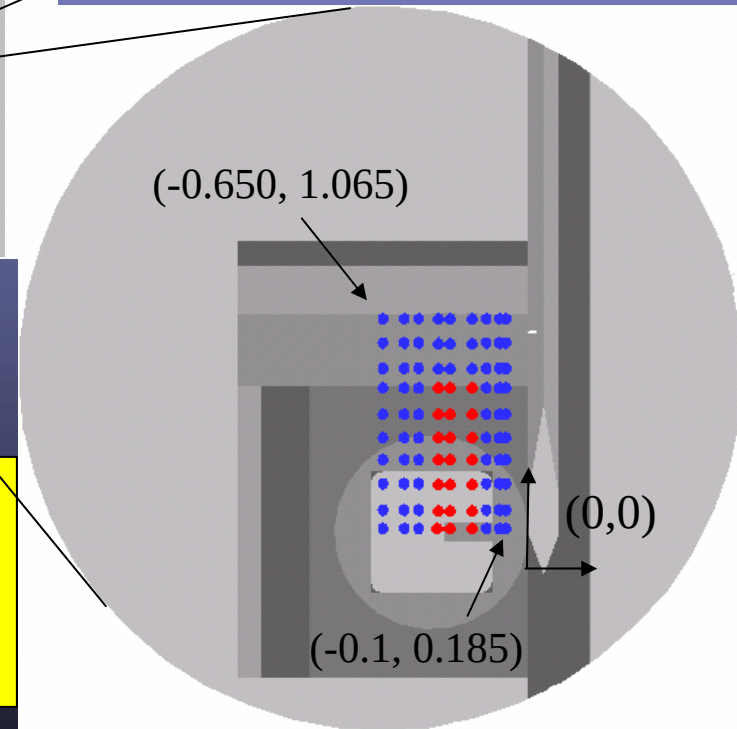
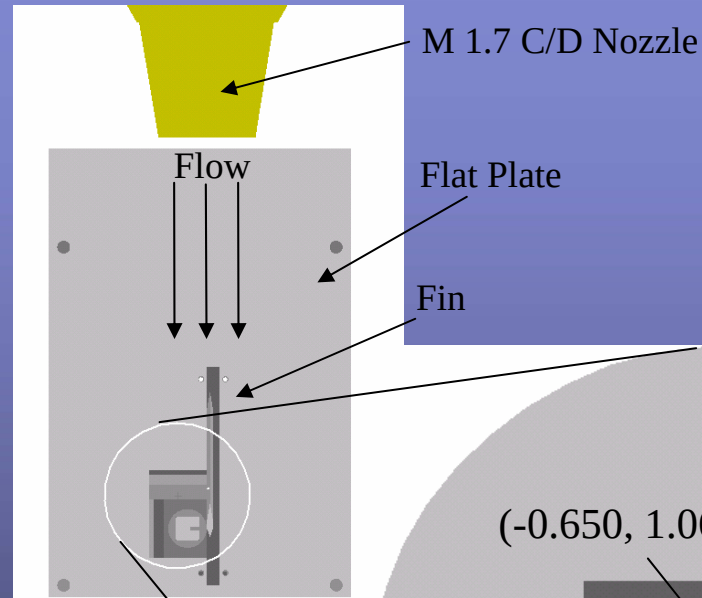
0.2 Round Pin

# Parametric Study Details

## Pin location test matrix

- 9 x 10 Matrix (90 locations)
- 0.55 in spanwise x 0.88 in streamwise
- Force measurements made for all pins at all points except trapezoid, which experienced structural failure
- 271 unique tests performed
- 1300 + data points (each location performed 3 times)

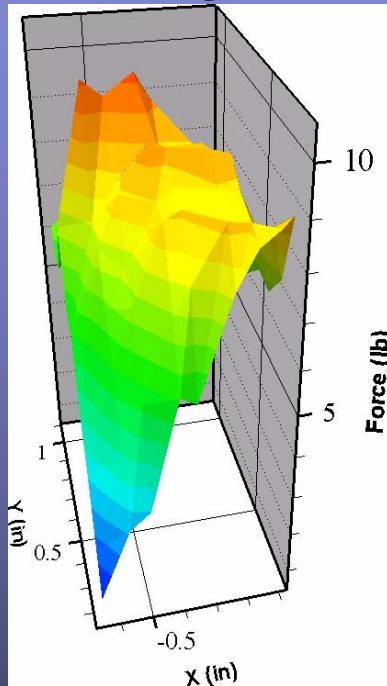
Forces on fin directly measured as opposed to pressure measurements



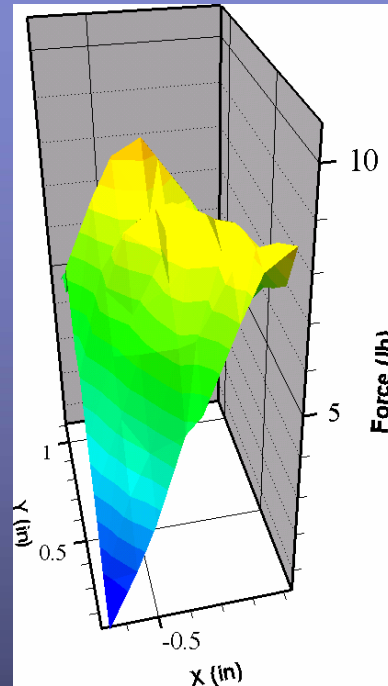
- Original Test Matrix (March 2003)
- ● Extended Test Matrix (March 2004)

# 3-D Contours of Force Data

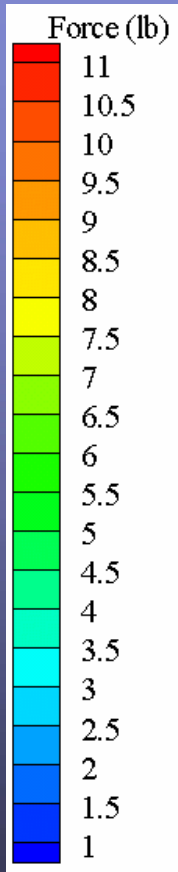
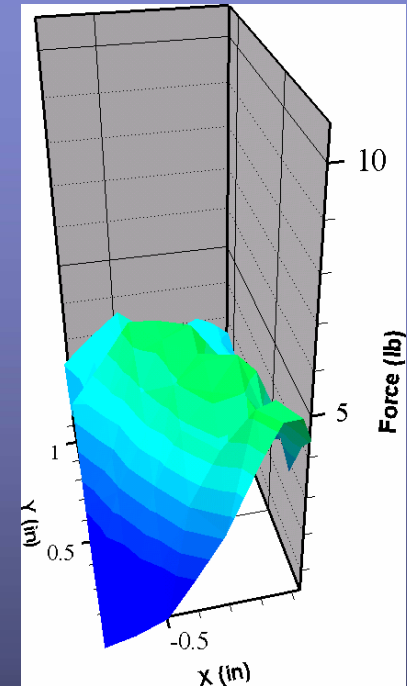
Rectangle 0.2



Round 0.2



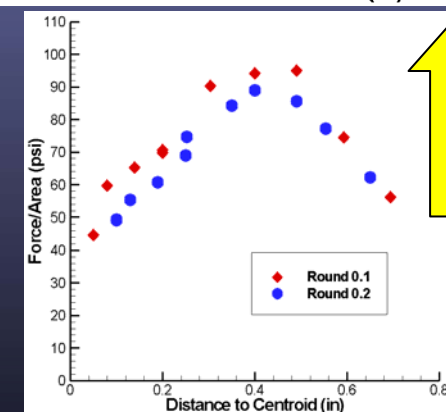
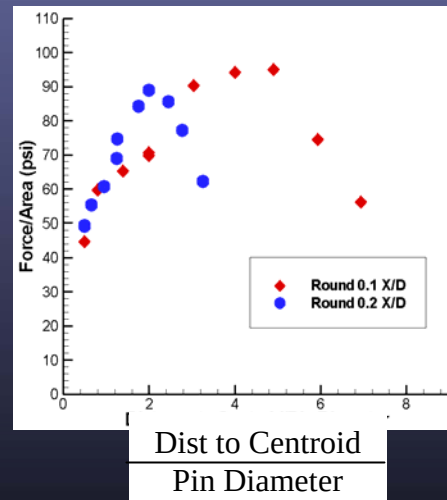
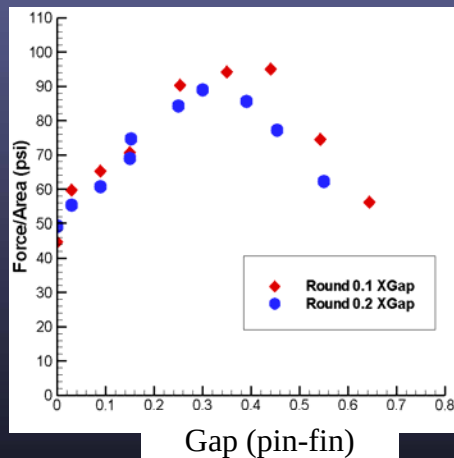
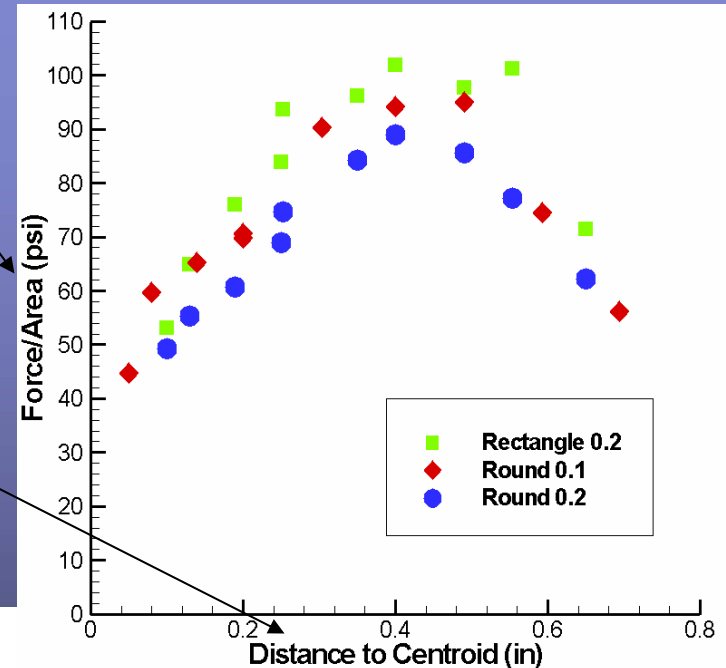
Round 0.1



- Contour plots of side force vs pin location show same trend for all pins
- Clear evidence of optimal regions for pin location
  - ➔ Implies there is leeway in placement of pin
  - ➔ Important as mechanical/space restrictions may not allow for location at optimal location
  - ➔ Relative force for flat pin larger than round with same frontal area
  - ➔ This likely due to stronger shock (no 3-D relieving effect)
- Hypothesis that optimal location should scale with pin diameter, was proven wrong (compare 0.1 and 0.2 dia pins)
  - ➔ The 3-D shock interactions are complex and do not lead to simple scaling

# Effect of Separation Distance (between pin and fin)

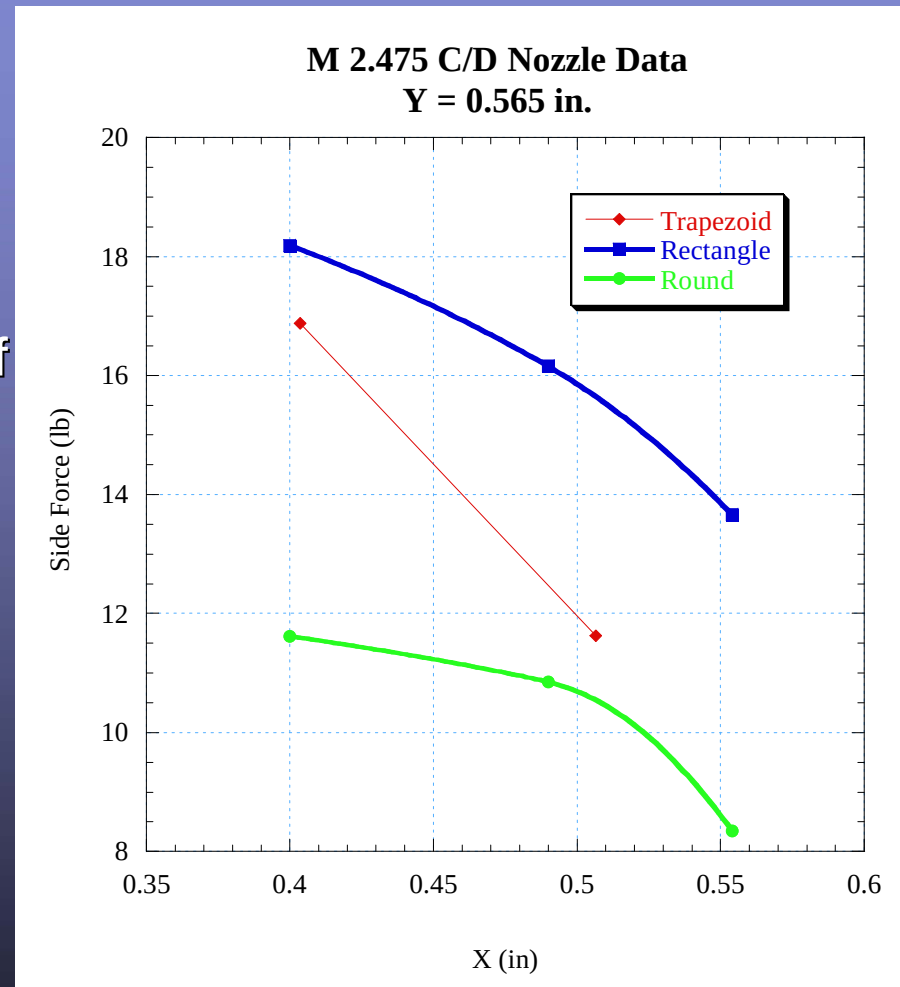
- Dividing the force by the frontal area of the pin provides a 1<sup>st</sup> order collapse of the magnitude
- Several different parameters were explored to determine the effect of separation distance
  - ➔ The distance from the edge of the fin to the centroid of the pin provided the best collapse
  - ➔ Optimum separation distance appears to be about 0.41-0.42 in
- Plots are at  $Y = 0.775$  in



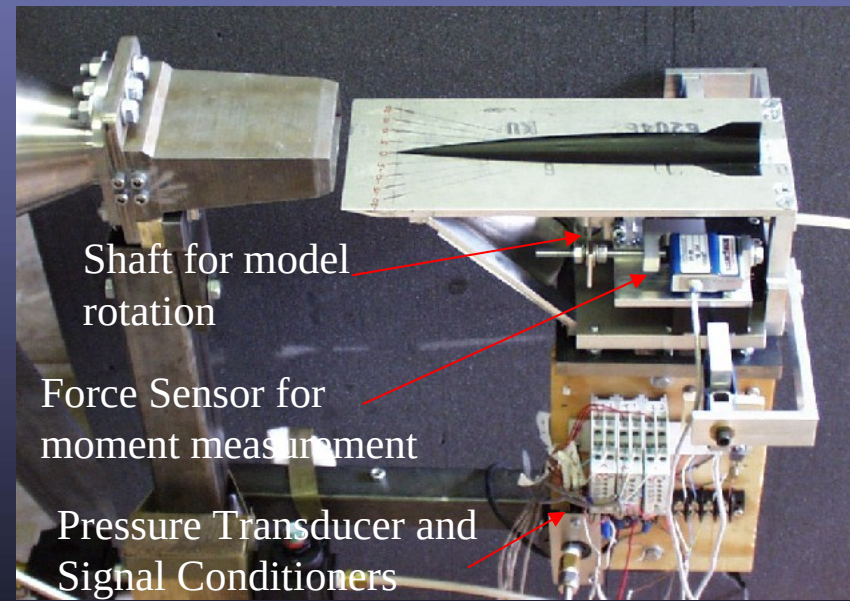
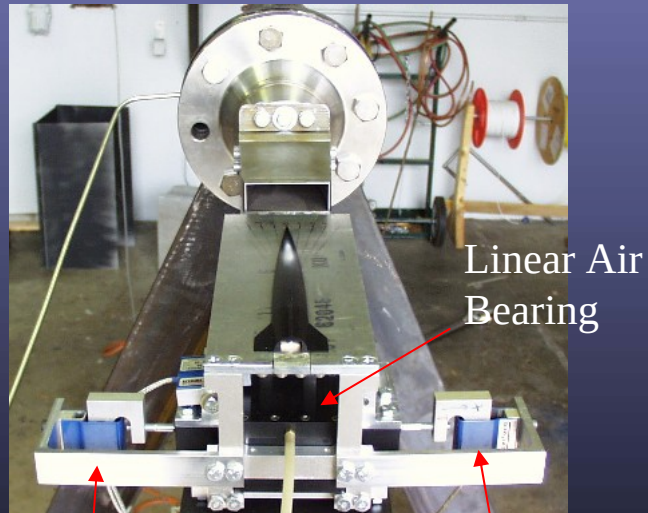
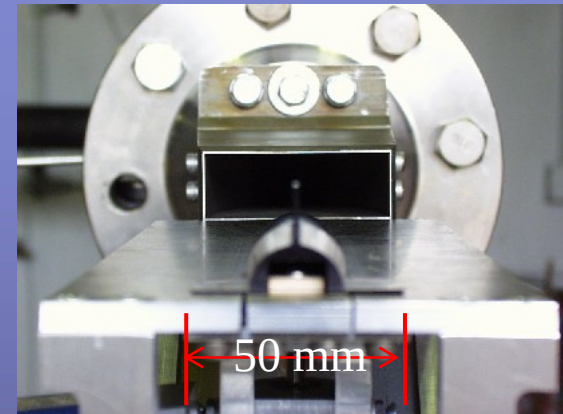
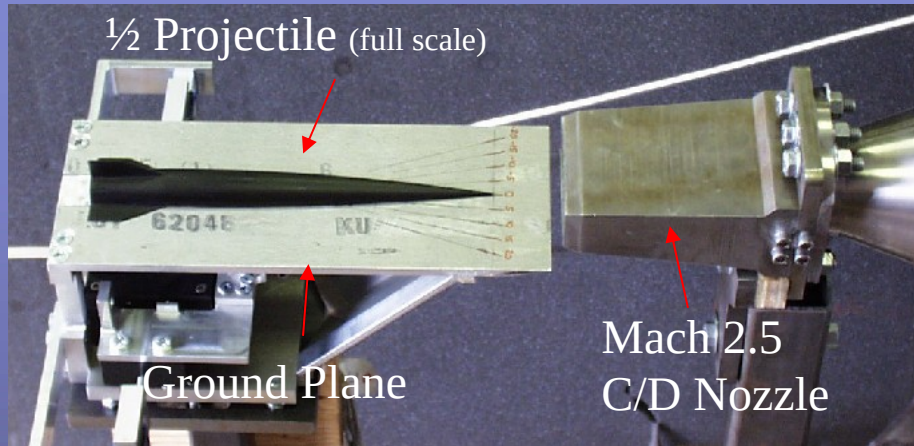


# Effect of Pin Geometry

- For same frontal area, rectangular pin gives most force
  - Has least 3-D relieving effect
  - Seems to outweigh additional sideforce generated on trapezoidal pin
- Optimal (X,Y) location independent of pin geometry
- Enough trapezoid data acquired (before structural failure) to demonstrate that flat pin is better

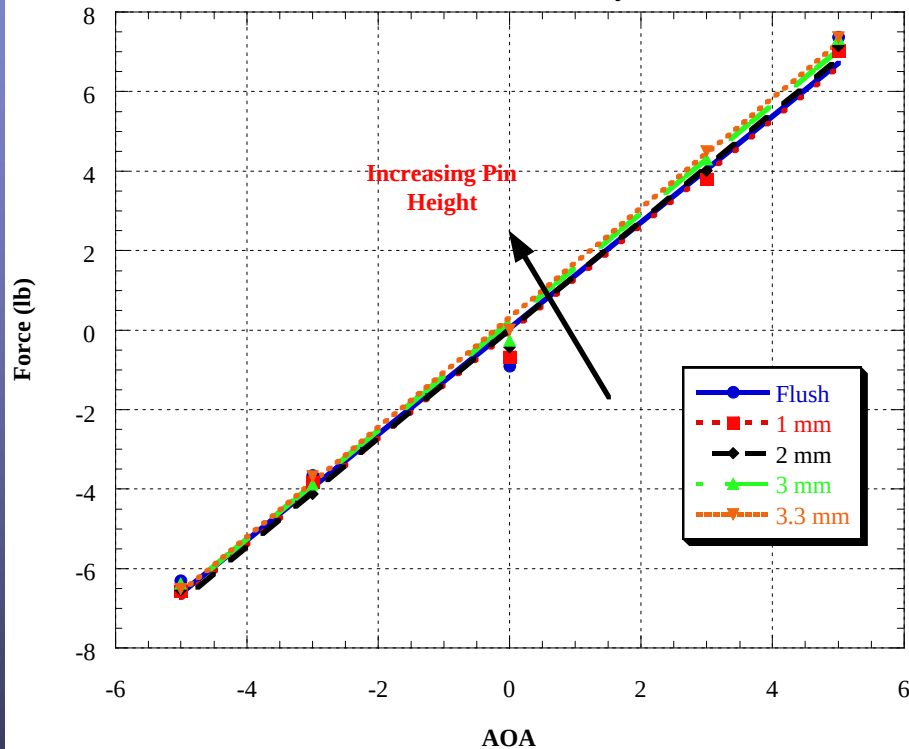


# Mach 2.5 Experiments at GTRI

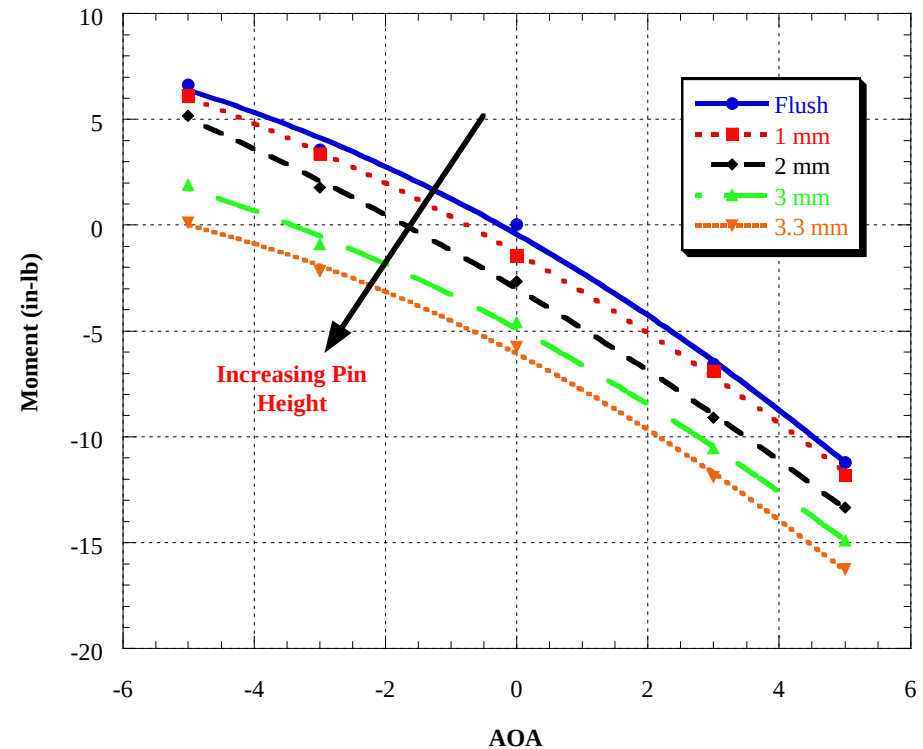


# Effect of Pin Height

Force on Projectile  
Trapezoid Pin 22.5 deg Orientation  
M = 2.47, Half Body



Moments Produced by Trapezoid Pin  
M = 2.47, Half Body, 22.5 deg Orientation



- Force dominated by AOA of projectile
- Non linear effect of pin height on moment
- Projectile should be rotate to about 5 degrees with pin deployed



# Second Generation Actuator Rotates into Flow

- Rocker Pin Hardware Installed in Wind Tunnel Scale Model

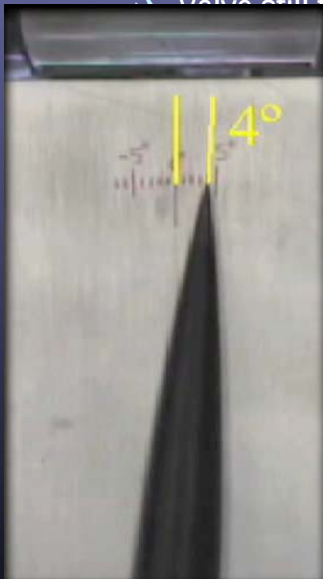
- Rotation solves stiction problem

- Consisted of

- Rocker Pin Assembly
  - Pneumatic Cylinder
  - Small Valve

- Further work needed

- Not g-hardened
  - Valve still too large



- Using 90 psi

- Very large holding force
  - Response time on order of 10 ms
  - Rotates projectile over 4 degrees

↑  
[Click to Play Movie](#)

# Experimental Input to CFD

## ■ Experiments showed

- Where to place guidance pins
- Effects of pin geometry
  - Including material failure (not from CFD)
- Crude force measurements
- Mechanical design considerations (not from CFD)

## ■ Need CFD to complete picture

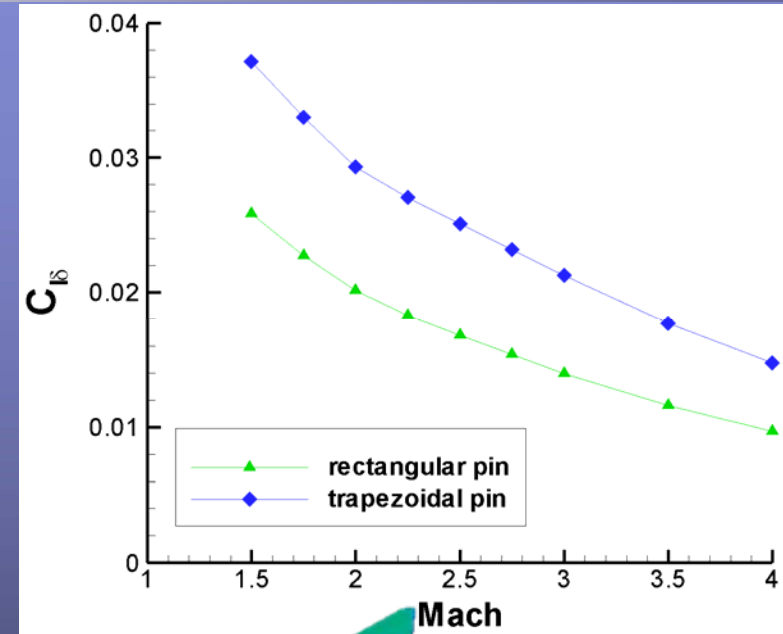
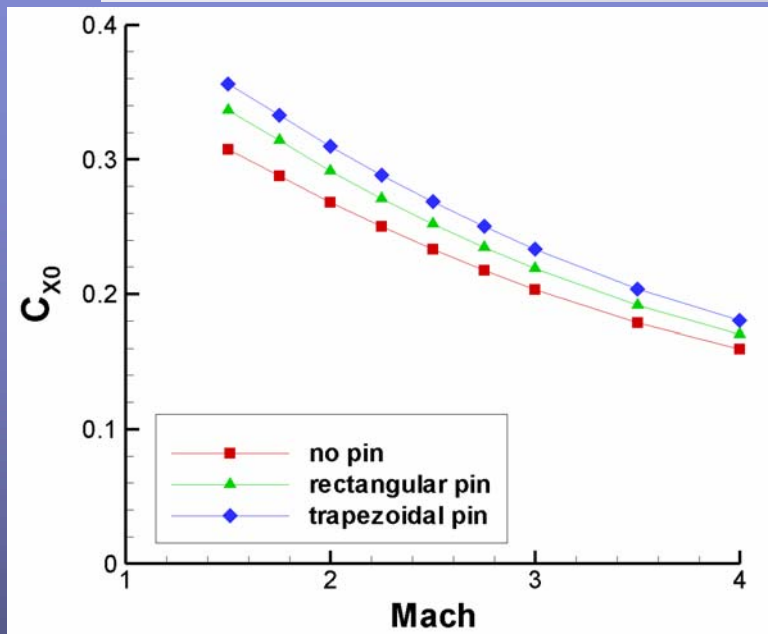
- Little flow understanding
- Better drag and force measurements
- Use full 3-D body

## ■ Combine EFD and CFD to predict Range Tests



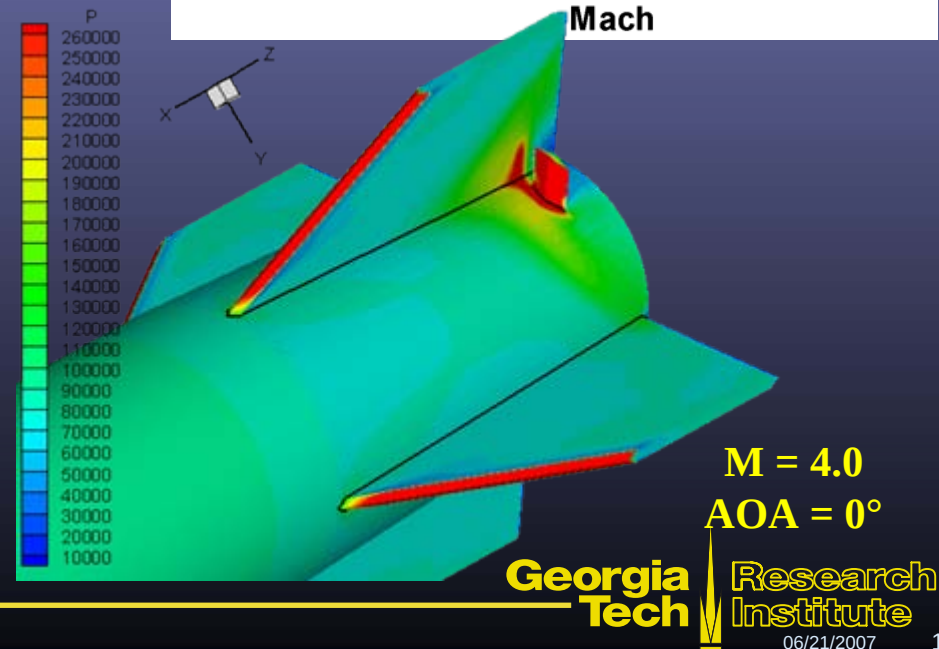


# Using CFD to Predict Range Test Results



## ■ Drag and Roll Torque Predicted using CFD

- ➔ Allowed for estimation of performance in range
- ➔ Fewer shots required as we knew how many rotations to expect downrange



# ARL Range Tests to Measure Roll Torque

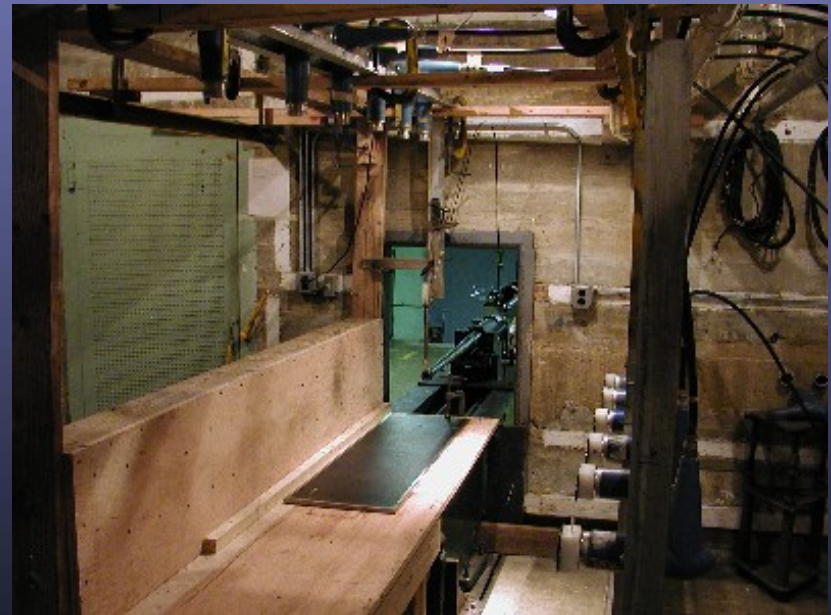
## ■ ½ Scale Projectiles Fired from 1 inch Gun

- Quantify Rolling Moments
- Provide Results for Validating CFD
- Provide More Accurate Aero Coefficients to 6 DOF

## ■ Total shots fired: 15 rounds

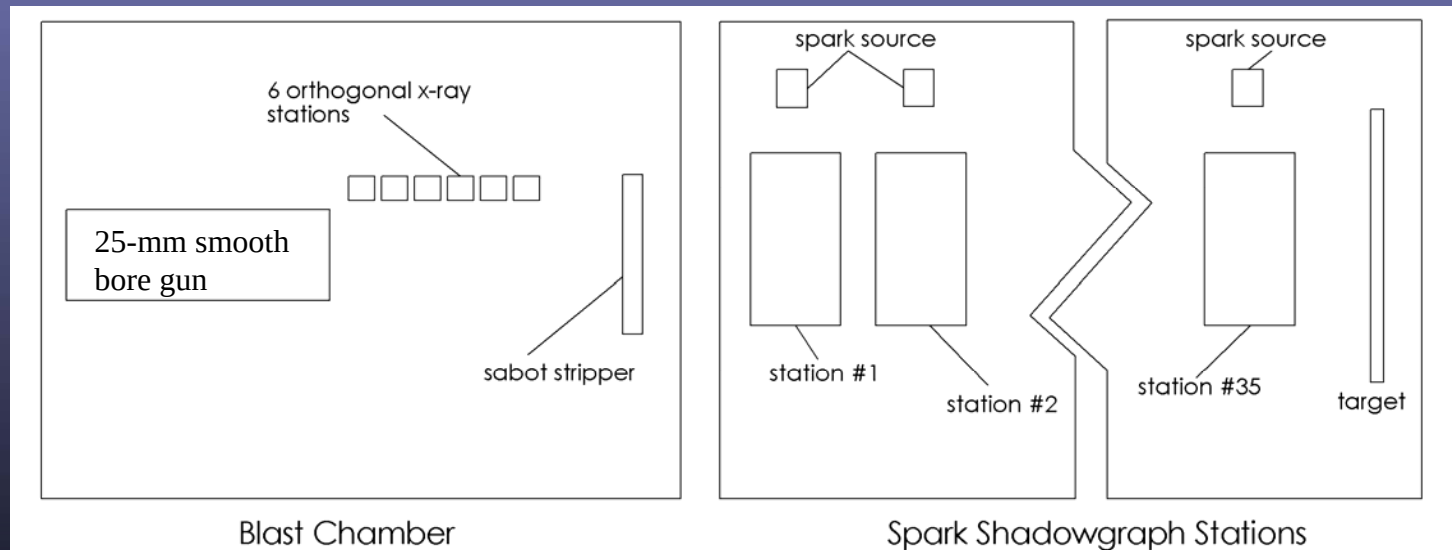
- 3 with no pins
  - 1 at Mach 3
  - 1 at Mach 2.5
  - 1 at Mach 2
- 3 with long pins (0.1 in height) at Mach 3
- 9 with short pins (0.07 in height)
  - 3 at Mach 3
  - 3 at Mach 2.5
  - 3 at Mach 2

Picture of test facility



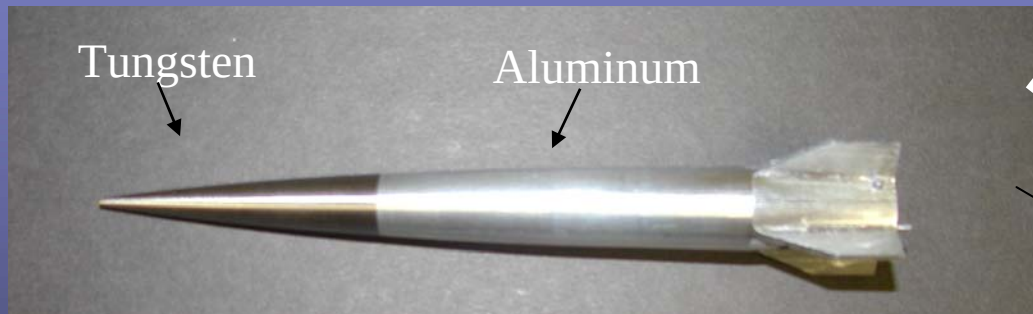
# ARL Range Test Setup

- 6 Orthogonal X-ray Stations Near Muzzle
  - ➔ Showed that Sabot Separated Cleanly
- 35 Shadowgraph Stations – to 100 m Downrange
  - ➔ Generated Images that were used to determine;
    - Roll and Pitch Damping
    - Drag
    - Number of Revolutions – Spin Rate

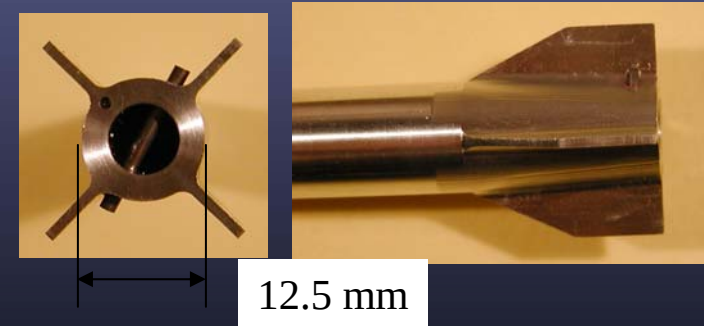


# Test Articles

- Projectiles ½ Scale (25 mm)
- Pins were round 1/16<sup>th</sup> in diameter on opposing fins
- Nylon Sabot

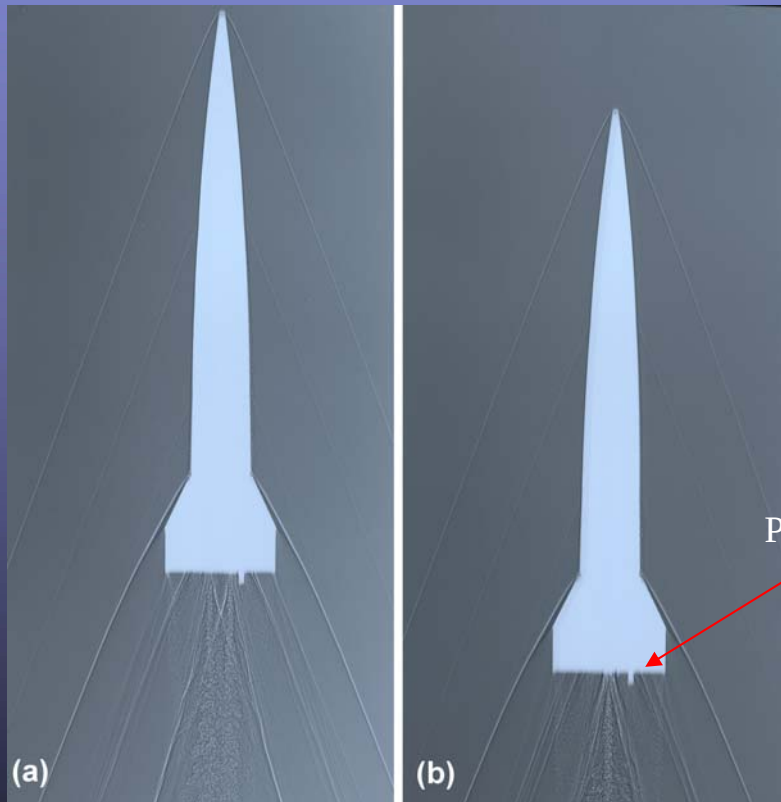


Short Pin Test Article



# Shadowgraphs from Range – Count Rotations

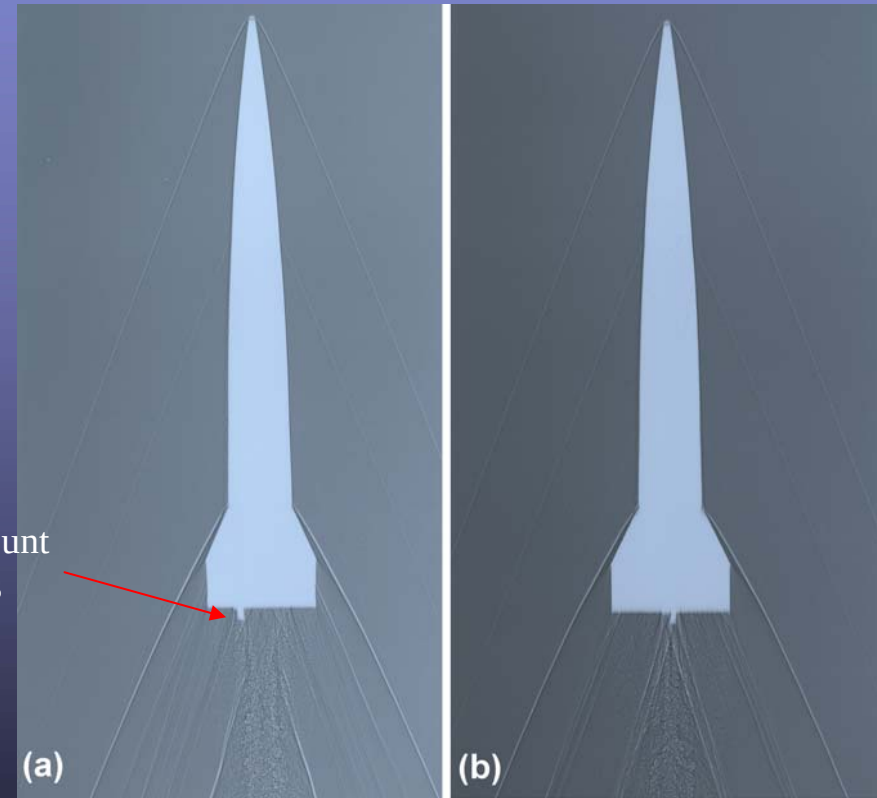
- The rotation of the round as it traverses the range can be tracked via a spin pin
- The rotation rate leads to a measurement of roll torque developed by pins



Stations 22 and 27

6.7m to 8.2m

Little Spin Observed



Stations 295 and 300

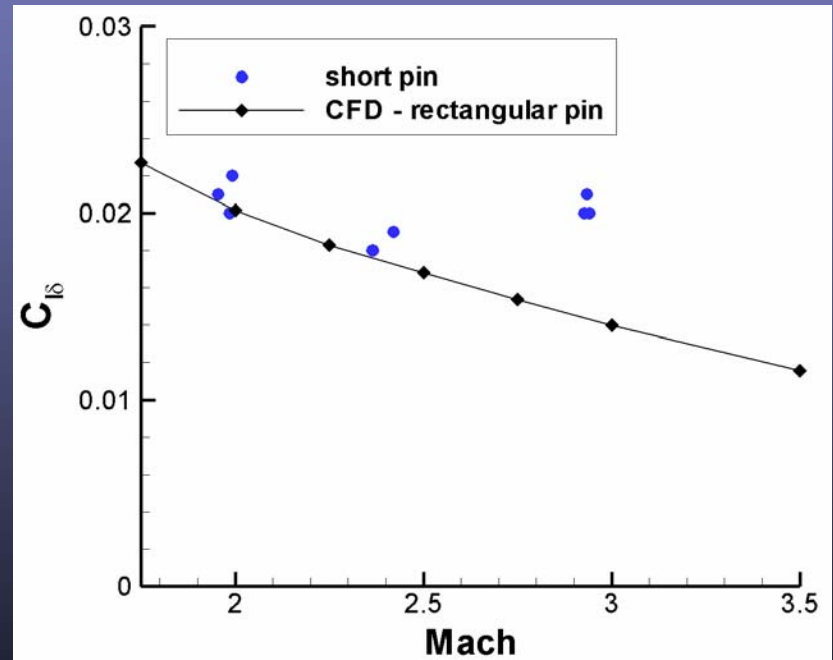
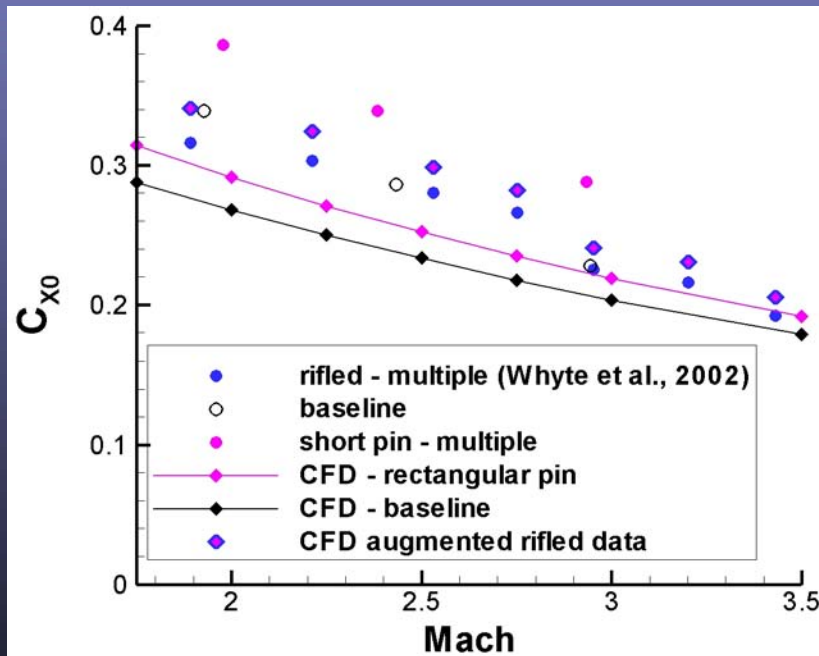
90m to 91.4m

Over 90° rotation



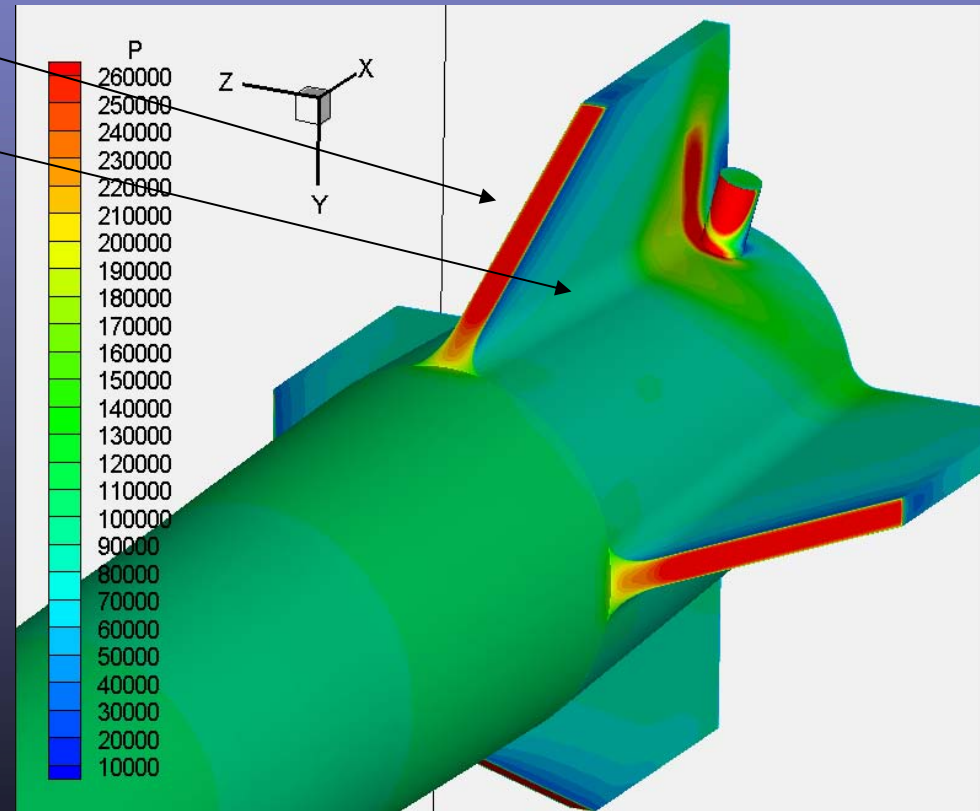
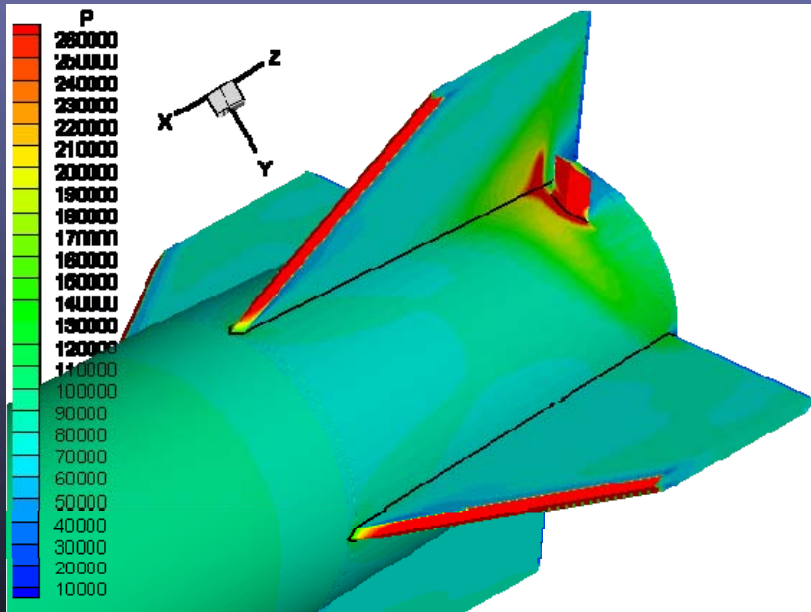
# Range Test Comparison with CFD

- Comparison with measured data not as good as expected
  - Drag under predicted at all Mach numbers
  - Roll torque prediction worse as Mach number increased



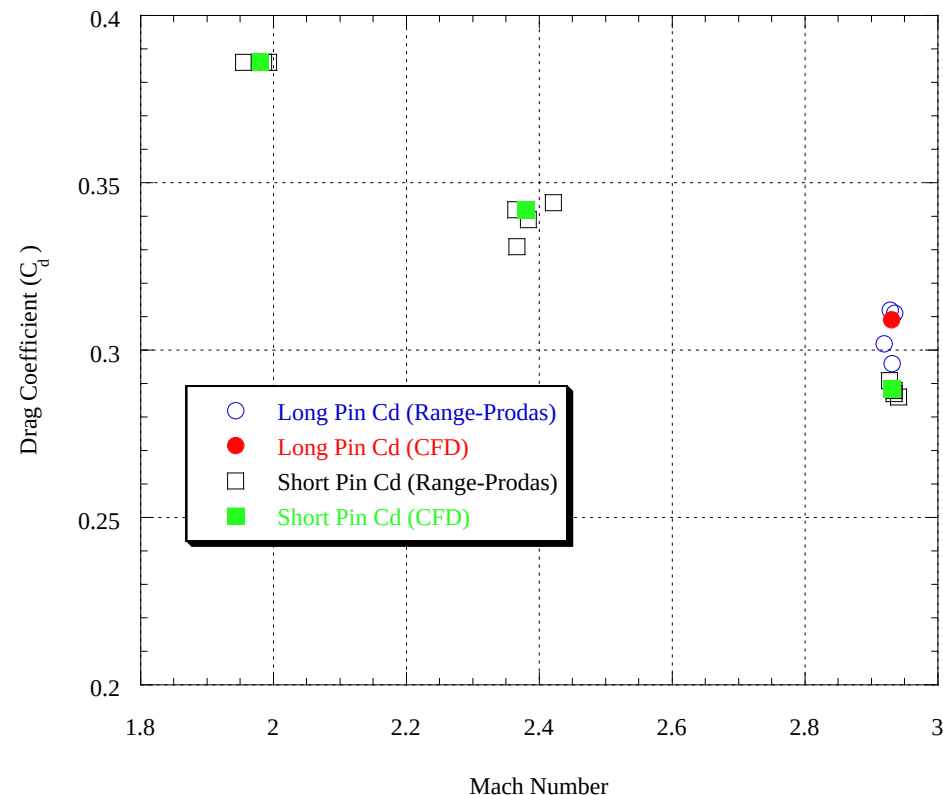
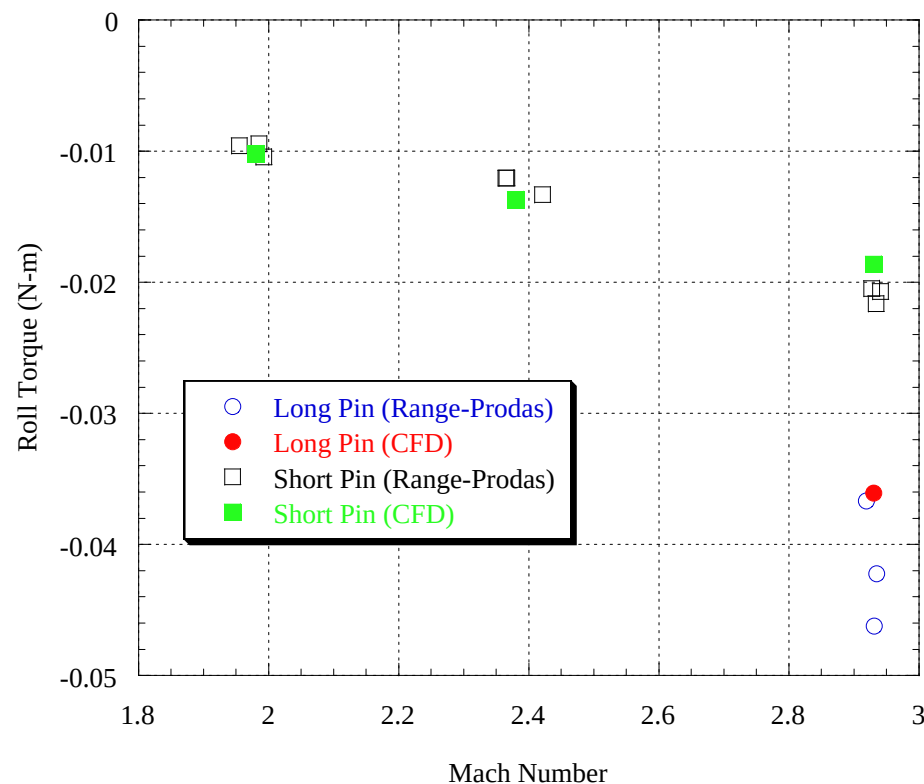
# What went wrong?

- Compromises in machining small rounds led to significant differences between CFD geometry and test rounds
- New grid generated and new runs accounting for
  - ➔ Fin leading edge bluntness
  - ➔ Fillet at base of fin
  - ➔ Round pin versus Rectangular



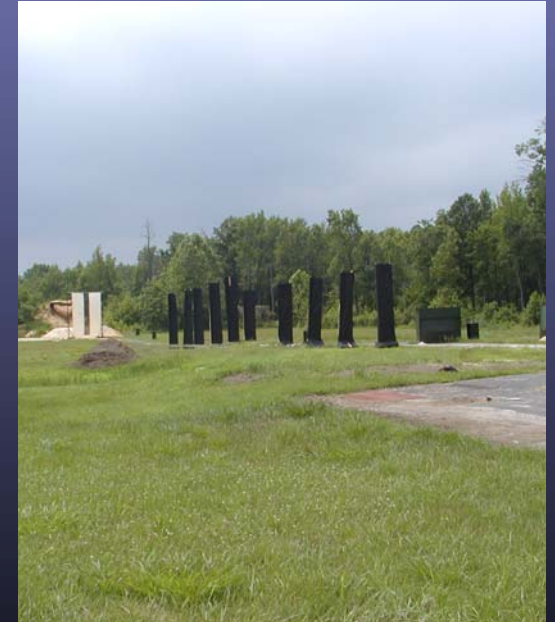
# Comparison with Updated Geometry

- Once a more accurate geometry was modeled, a much better correlation was found between the computed and measured drag and roll torques
- Allowed us to proceed with divert test on full scale rounds



# 700 ft Range Preliminary Tests

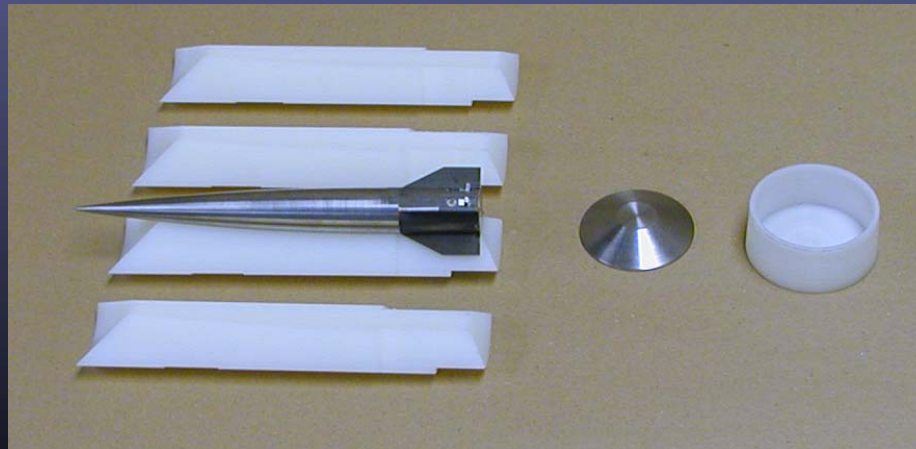
- Outdoor Range
- 75 mm smooth bore gun
- Yaw cards set up
- Problems encountered
  - Stability
  - Sabot Separation





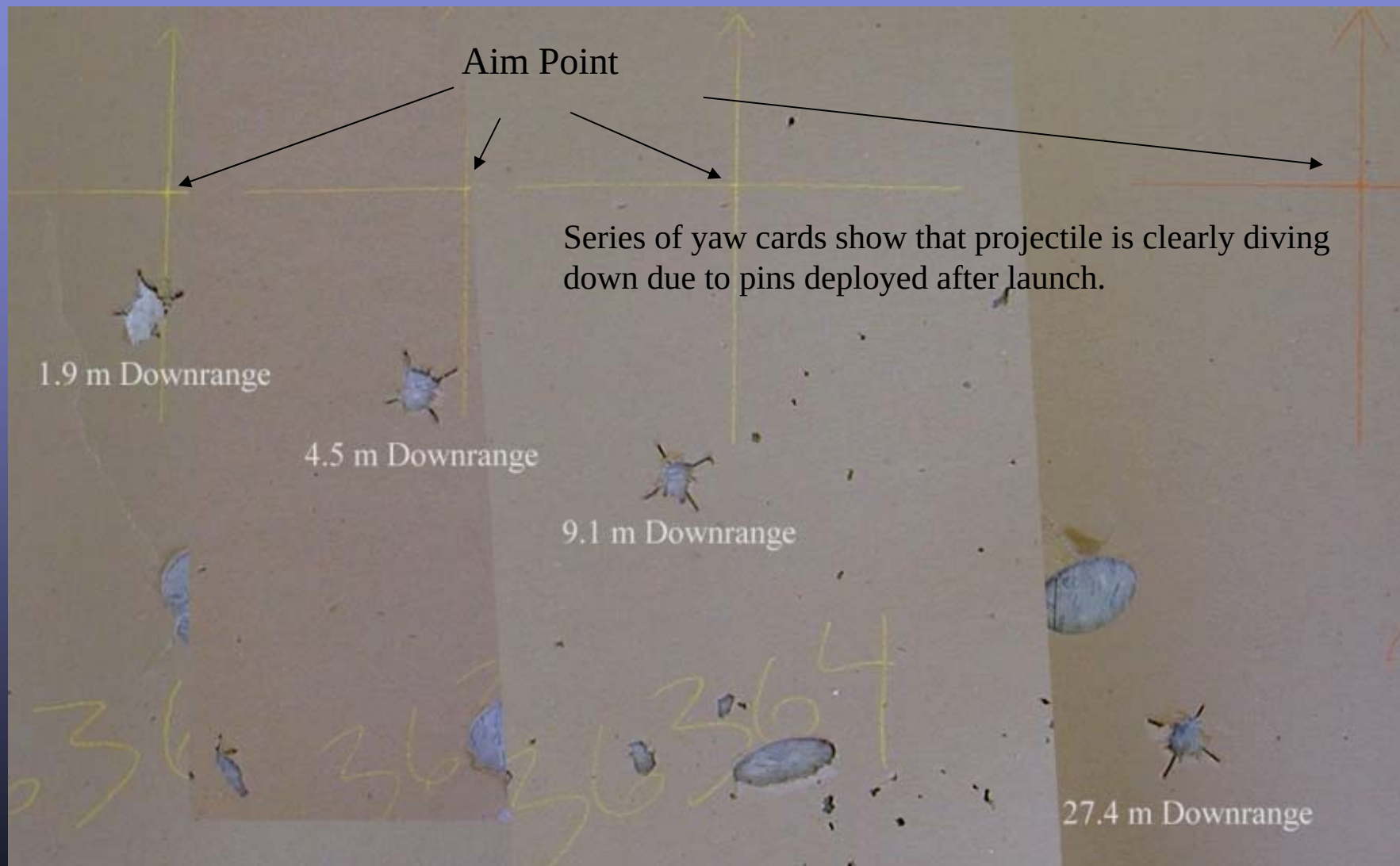
# Sabot and Launch Package Resolution

- New set of rounds made with increased static margin
- Cup scored more deeply
- Aluminum pusher plate



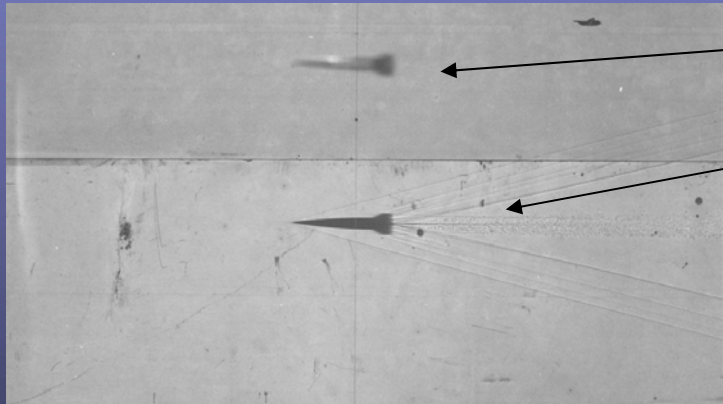


# 700 ft Range Tests – Divert Demonstration

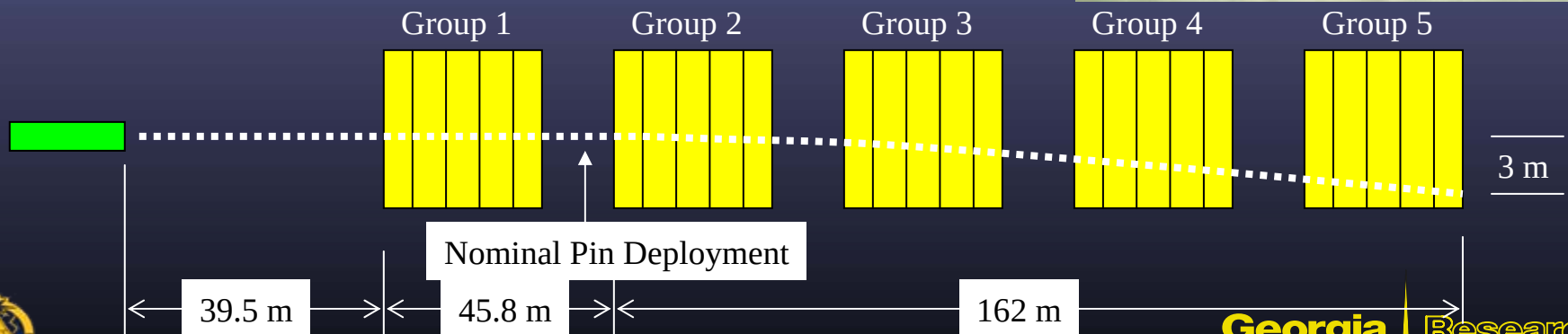


# Transonic Spark Photograph Layout

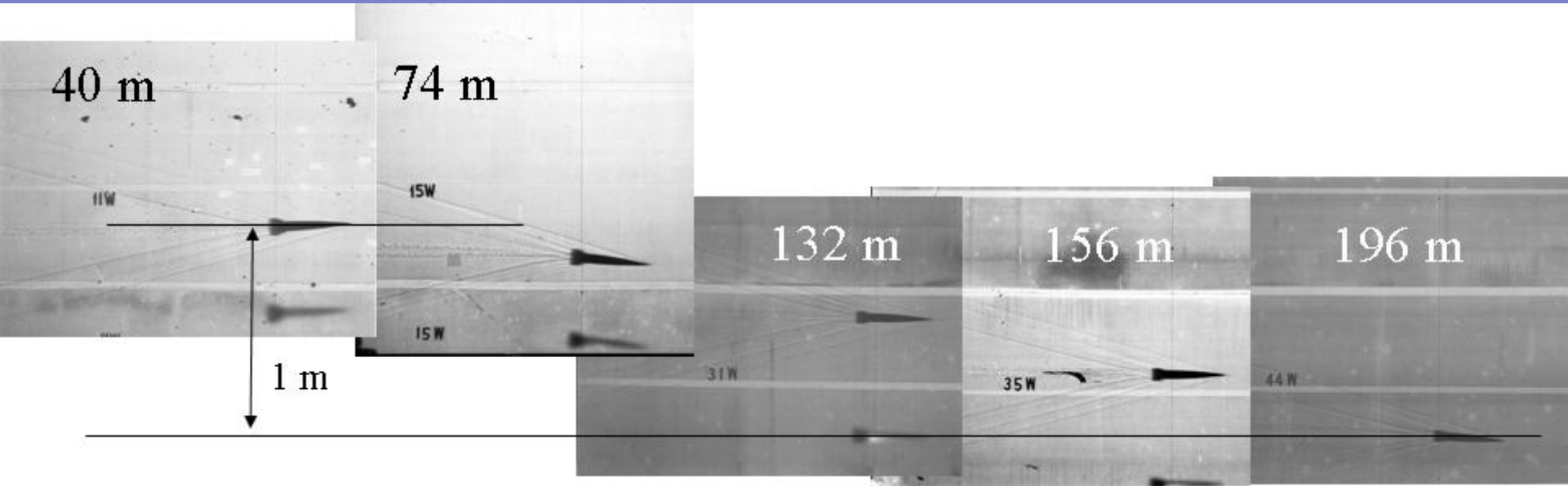
- 5 groups of 5 stations
- Each Station provides Shadowgraphs for
  - ➔ Vertical Plane – Wall
  - ➔ Horizontal Plane - Pit



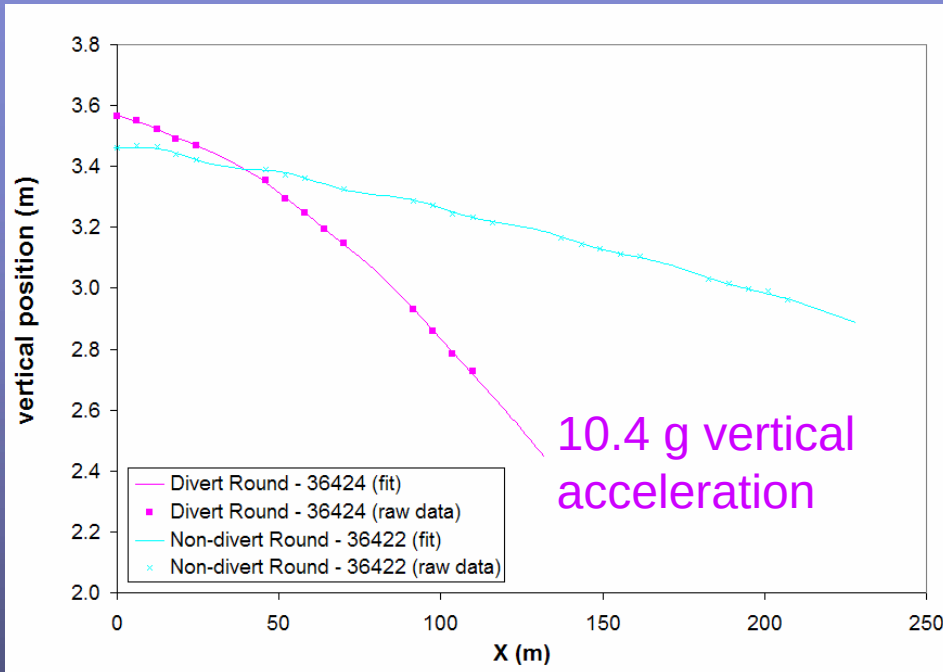
Projectile  
Shadowgraph



# Divert Demonstrated by Shadowgraphs



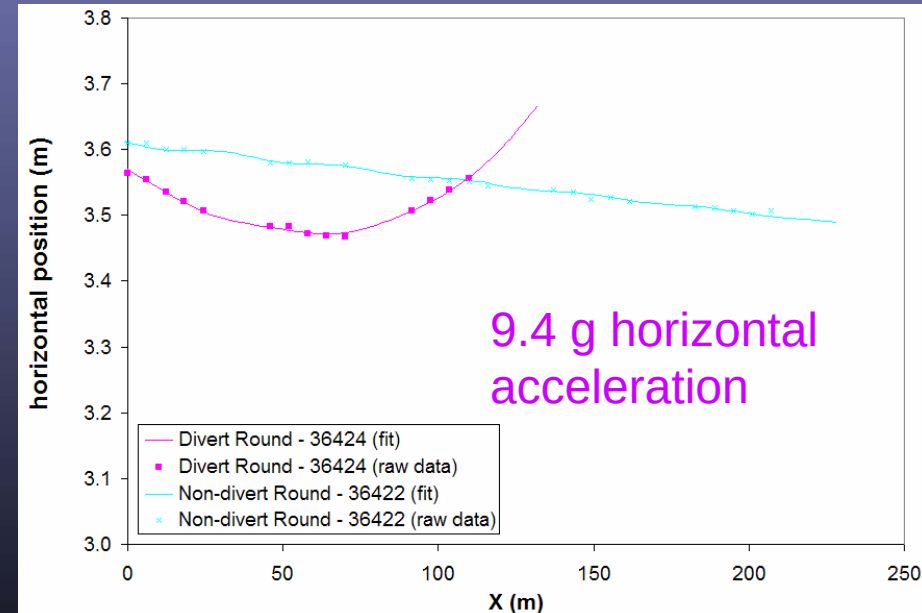
# Demonstrated High G Turn on Stable Projectile



Stable projectile for testing (1.5 caliber static margin)

~14 g divert maneuver

~80 N force created by control pins



Preliminary data reduction

More data will be available in the near future

Concept promising for high g maneuvers



# Conclusions

- A demonstration of steering a Mach 4 projectile using the guidance pins was successful
- The combined CFD and Experimental efforts led to a greater understanding of the effects of the pins
  - EFD and CFD each used to get different but required forces and moments
    - Results could have been easily done without IFD
  - This in turn allowed us to better predict the results of the range tests
- Less range tests were required because once the predictions were validated, it was proven we understood the aerodynamics
  - This saved substantial amounts of money
    - \$10,000 bullets and 5 range operators and 2 PhDs add up fast
    - (As does destruction of the ADT alarm box)

Less Bullets → Less \$\$ → IFD=GOOD

