Assessment of Lifting Body Linear Aerospike Plume Effects on Vehicle Aerodynamics

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The lifting body/linear aerospike is one of three configurations being studied for an SSTO vehicle. A preliminary aerodynamic database existed for then current lifting body configuration, however, this data base was developed without considering plume effects. A combined effort by the Computational Fluid Dynamics and Experimental Fluids Dynamics Branches was undertaken to determine first order effects of plume/external flow interactions on vehicle aerodynamics of this lifting body/linear aerospike configuration. Of interest were plume pumping/entrainment at low Mach numbers and plume induced separation of flow over the vehicle at higher altitudes. The CFD analysis included combinations of four Mach numbers, two angles of attack and four throttle settings. The majority of the CFD was two dimensional centerline analysis of the lifting body/aerospike. Incremental plume effects were derived by comparing the power-on, power-off, and throttled cases and were extrapolated to the preliminary aerodynamic database.

The plume had little effect on the vehicle aerodynamics for supersonic freestream velocities. At subsonic freestream velocities, the plume affected the vehicle aerodynamics through both jet pumping/entrainment and the jet flap effect.

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Overview

- Introduction
- Objective and Approach
- 2D CFD Results
- Application of CFD
- Conclusions

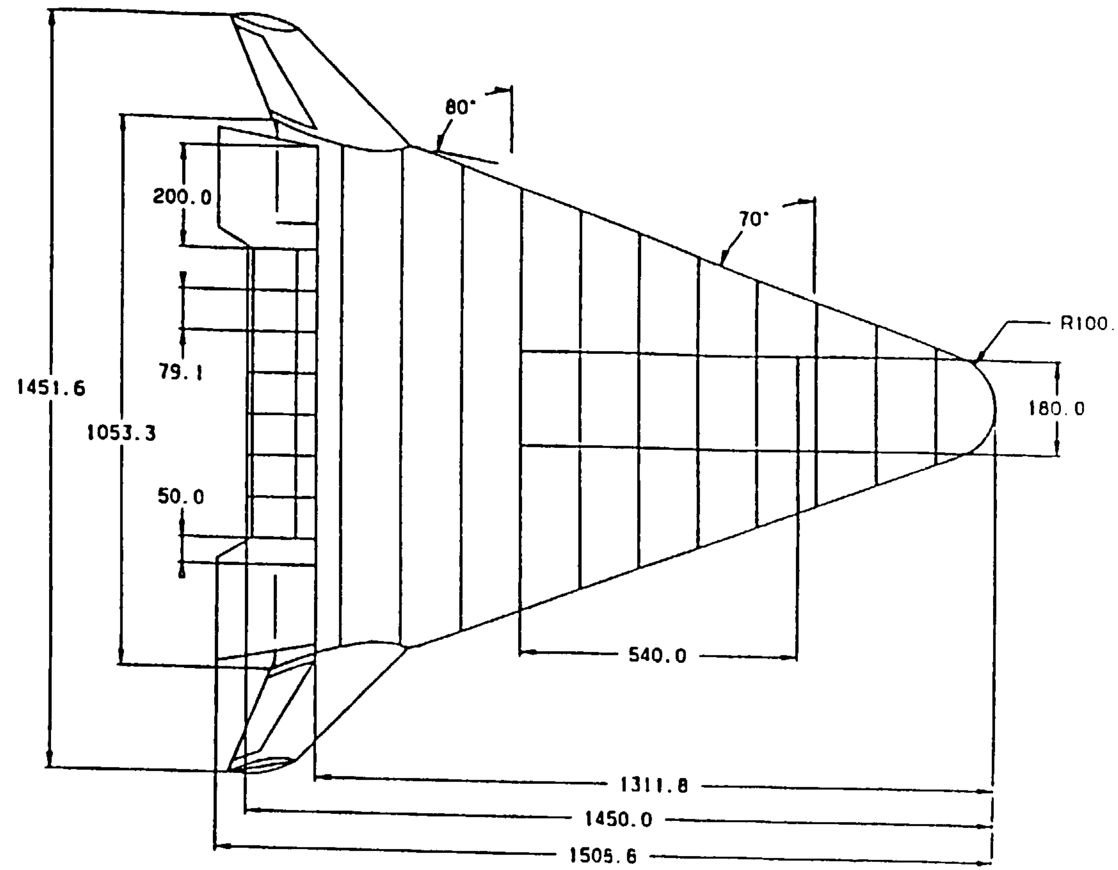
Introduction

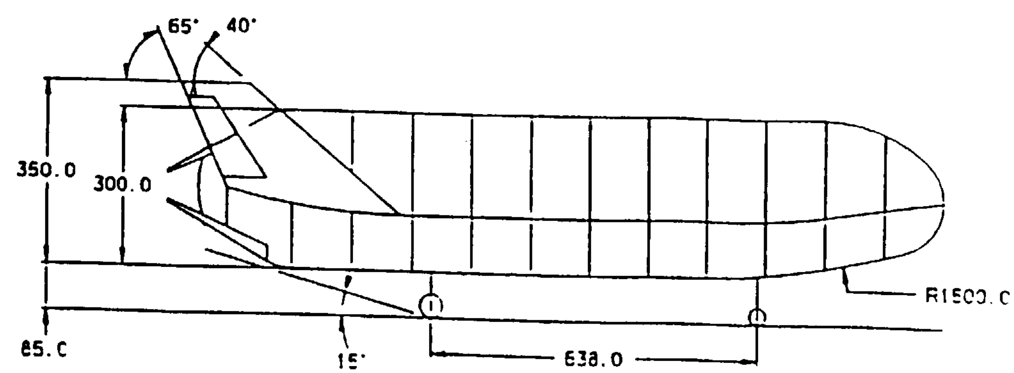
- **Lifting body with integrated linear aerospike is one of the three candidate configurations for X33/RLV.**
- **The then current lifting body configuration was the Lockheed K10.**
- **A preliminary aerodynamic database w/o plume effects and a preliminary flight trajectory existed.**
- **Because of vehicle configuration and close proximity of plume to vehicle, it was felt there were potential plume/external flow interactions.**
  - Subsonic/low altitude - plume entrainment/jet pumping
  - Supersonic/medium and high altitude - plume induced separated flow on vehicle (a la, Saturn, Shuttle)

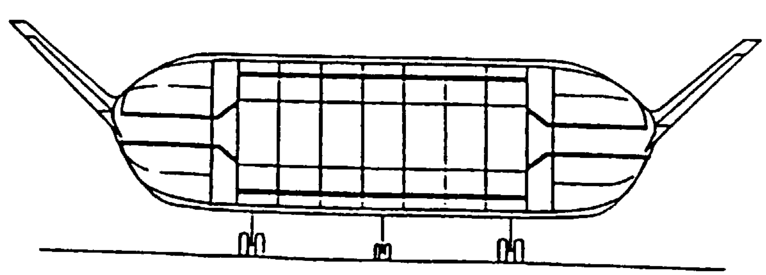
CONFIGURATION K-10

Sref = 5,600 sq. ft.
Swet = 13,100 sq. ft.

Total Internal Volume = 67,000 cu. ft.
Main Hyd. Tank Volume = 47,500 cu. ft.
Fwd LOX Tank Volume = 5,200 cu. ft.
Aft LOX Tank Volume = 12,700 cu. ft.







LOOKING FORWARD

Objective

Determine first order effects of plume/external flow interactions on vehicle pitch plane aerodynamics to generate plume effect increments for the aerodynamic database.

Approach

- **Performed series of 2D CFD analyses of K10 centerline to determine vehicle aerodynamics at different flight conditions.**
  - Three Mach numbers: 0.6, 1.2, 3.0
  - Power-off, power-on, power-on-throttled
  - Two angles of attack: 0 and 6 degrees

- **Two Dimensional analysis was chosen for several reasons.**
  - Short deadline for decision on a flight test.
  - 3D geometry quite complex. Long turn around time for above parametrics with 3D CFD.
  - 2D would allow for many more cases to be perform in the parametric study.
  - 2D analysis would exaggerate plume/vehicle flow interaction - conservativism (axisymmetric calculations could also be run as lower bound on interactions).
  - The centerline pressure coefficients could be extrapolated to 3D vehicle.

Assessment of Lifting Body/Linear Aerospike Plume Effects on Vehicle Aerodynamics

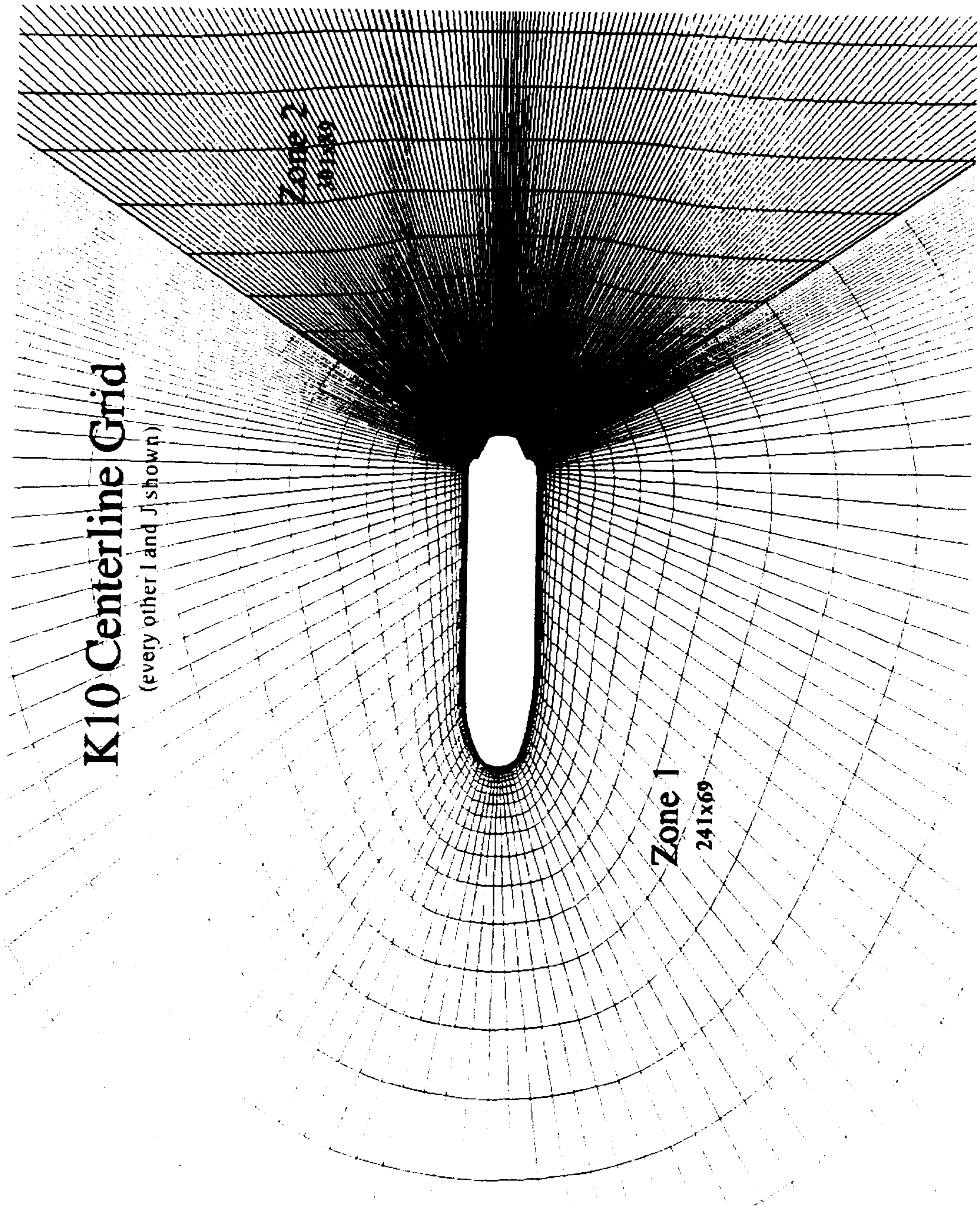
	Two Dimensional							
Freestream Mach	0.6		1.2		3.0		5.0	
A.O.A.	$\alpha=0$	$\alpha=6$	$\alpha=0$	$\alpha=6$	$\alpha=0$	$\alpha=6$	$\alpha=0$	$\alpha=6$
Throttle Setting								
Power -off	x	x	x	x	x	x	x	
Power - on	x	x	x	x	x	x		
Power -on -throttled								
70%/130%	x	x						
130%/70%		x						

Approach, cont.

- **Grid(s)**
  - Vehicle centerline profile was extracted from 3D surface grid.
  - 2D grid generated with GENIE, refined with GEN2D. Two zone grid, one for forward part of vehicle, one for vehicle base/aerospike. 43000 points total.
  - Different grid wall spacing for each freestream Mach number for acceptable y+'s.

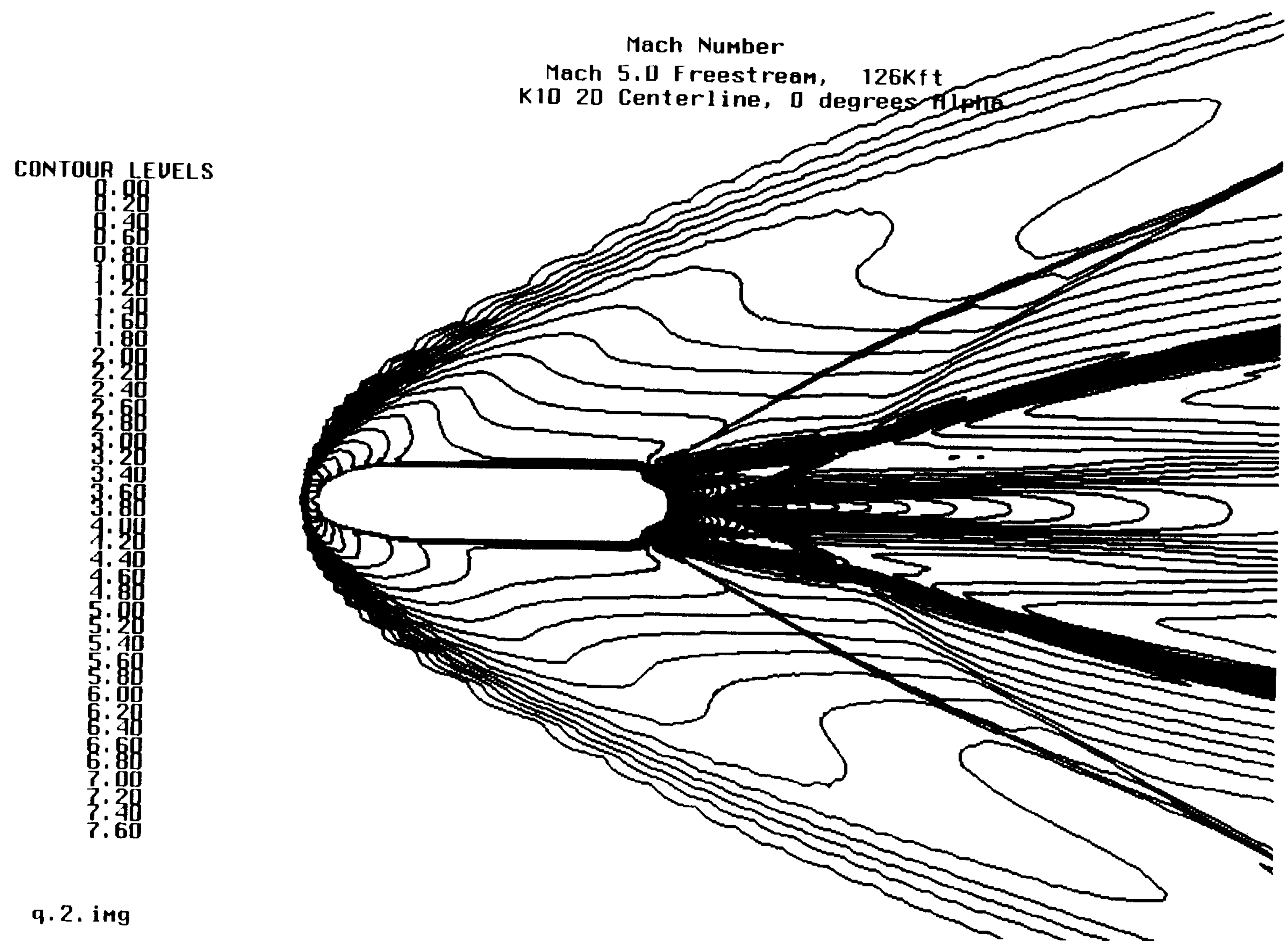
- **CFD**
  - GASP v2.3, Baldwin Lomax
  - Frozen flow, two species: air and a hot gas. Hot gas was average properties of exhaust products.
  - Convergence based on vehicle pressure coefficients reaching steady state.
  - CPU hours required varied from 0.5 to 15 hrs. Typical was about 8 hrs.

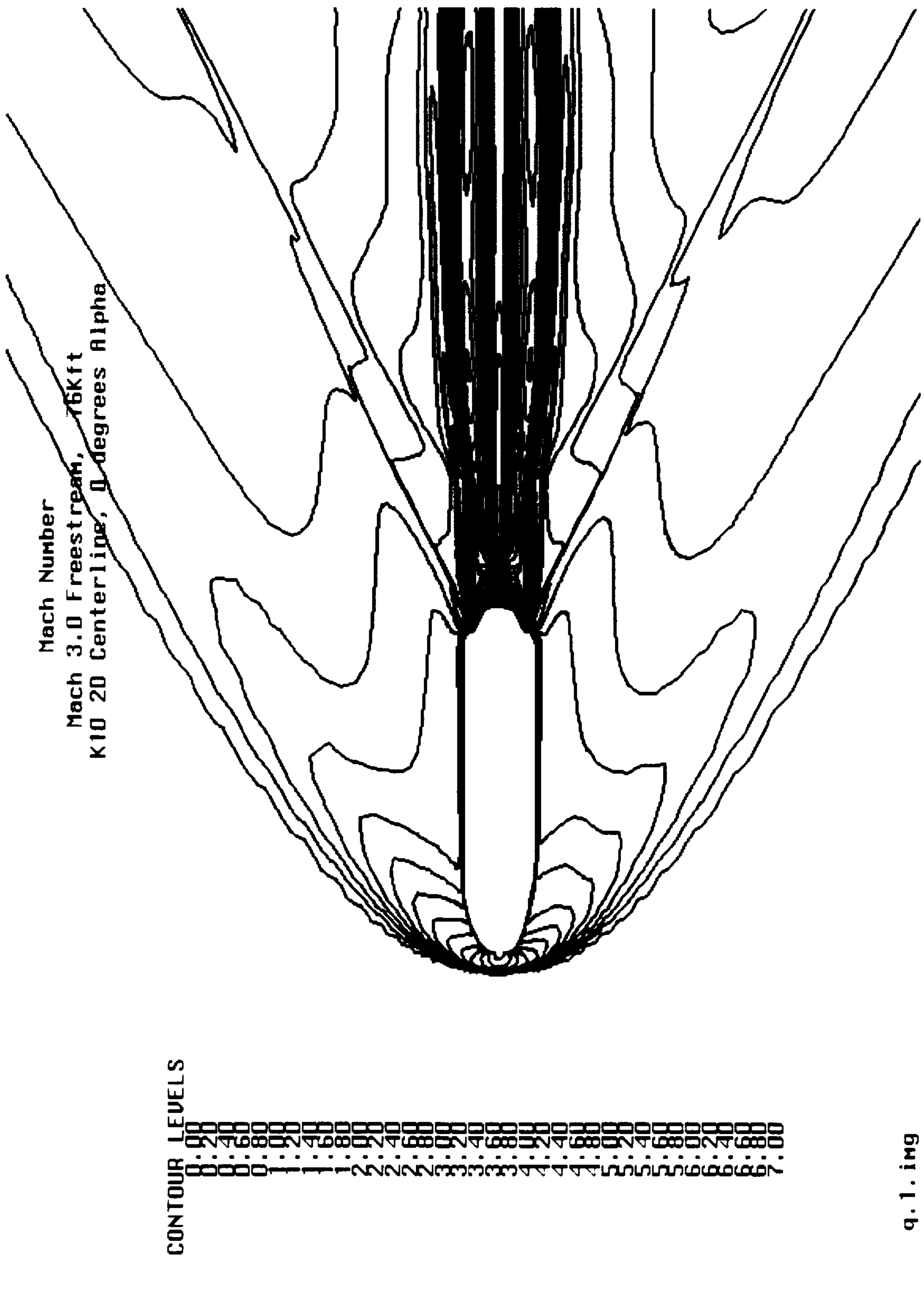
- **Derivation of plume effect increments**
  - Compared power-on, power-off and throttled cases to generate plume effect increments to preliminary data base.
  - Centerline 2D pressure deltas were applied to limited areas of total vehicle and extrapolated for the actual 3D geometry.
  - Incremental pressure distribution was integrated to determine total aerodynamic force and moment coefficients.


K10 Centerline Grid
(every other I and J shown)
Zone 2
Zone 1
241x69

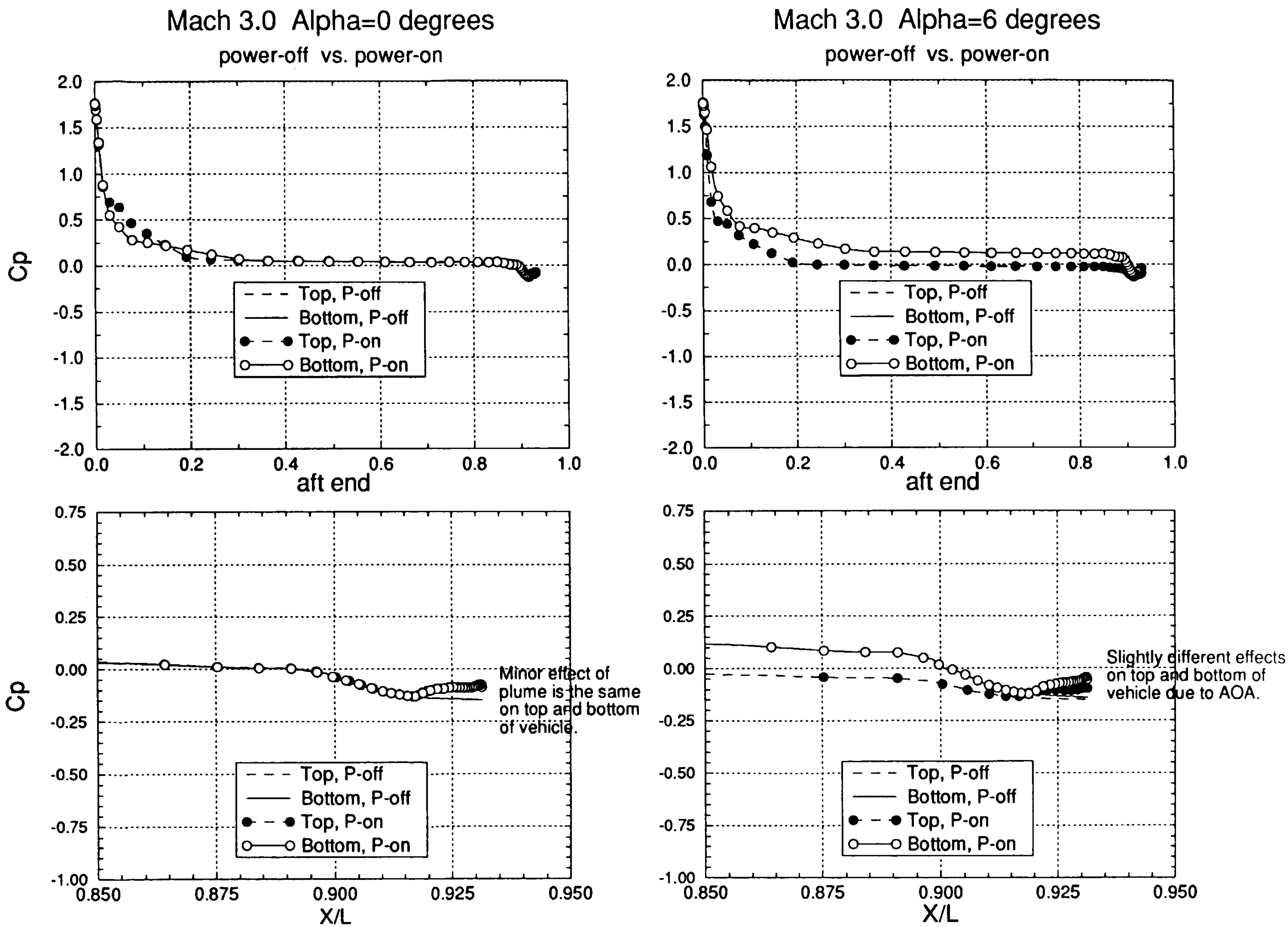
CFD Results

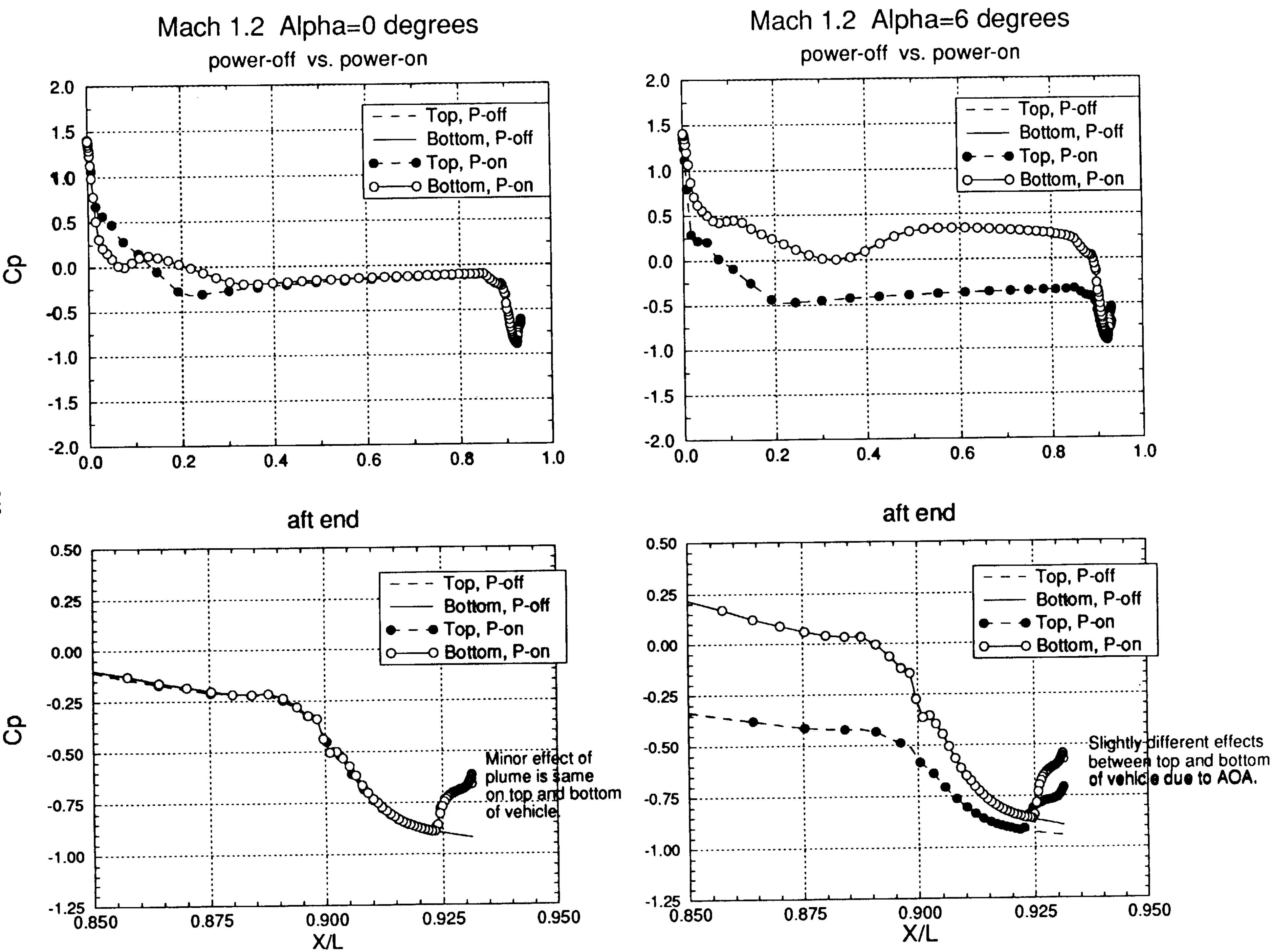
- **Mach 5.0 ~ 124Kft**
  - no significant plume billowing present
  - no significant plume induced separation on the vehicle
- **Mach 3.0 ~ 76Kft**
  - no significant plume billowing
  - no significant plume induced separation on the vehicle
- **Mach 1.2 ~ 31Kft**
  - no significant plume effects
- **Mach 0.6 ~ 12Kft**
  - 0 degree α power-on vs. power-off
    - » minor effect seen
  - 6 degree α power-on vs. power-off
    - » significant plume effects through plume entrainment and jet flap effect

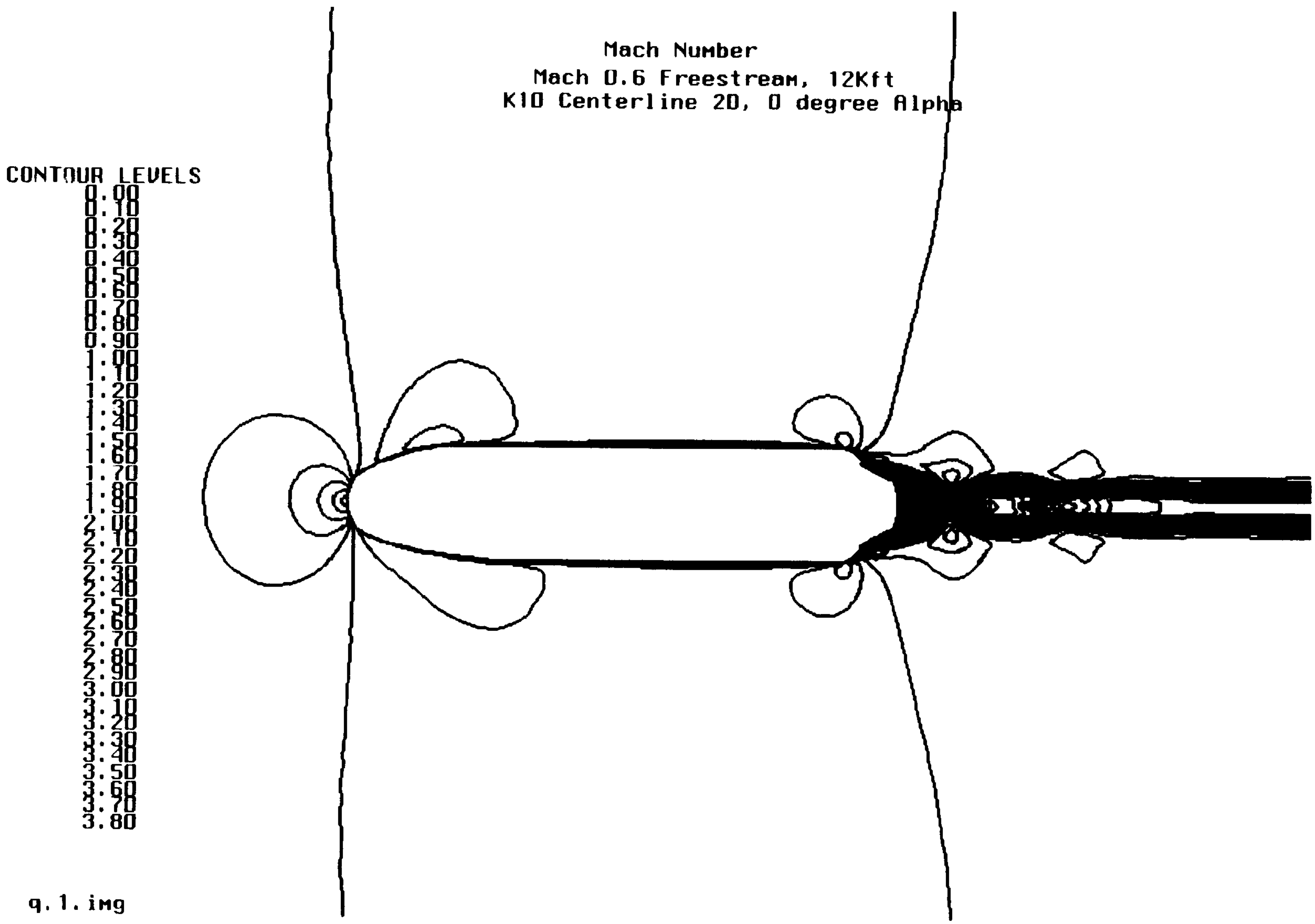

Mach Number
Mach 5.0 Freestream, 126Kft
K10 2D Centerline, 0 degrees Alpha
CONTOUR LEVELS
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00
2.20
2.40
2.60
2.80
3.00
3.20
3.40
3.60
3.80
4.00
4.20
4.40
4.60
4.80
5.00
5.20
5.40
5.60
5.80
6.00
6.20
6.40
6.60
6.80
7.00
7.20
7.40
7.60
q.2.img

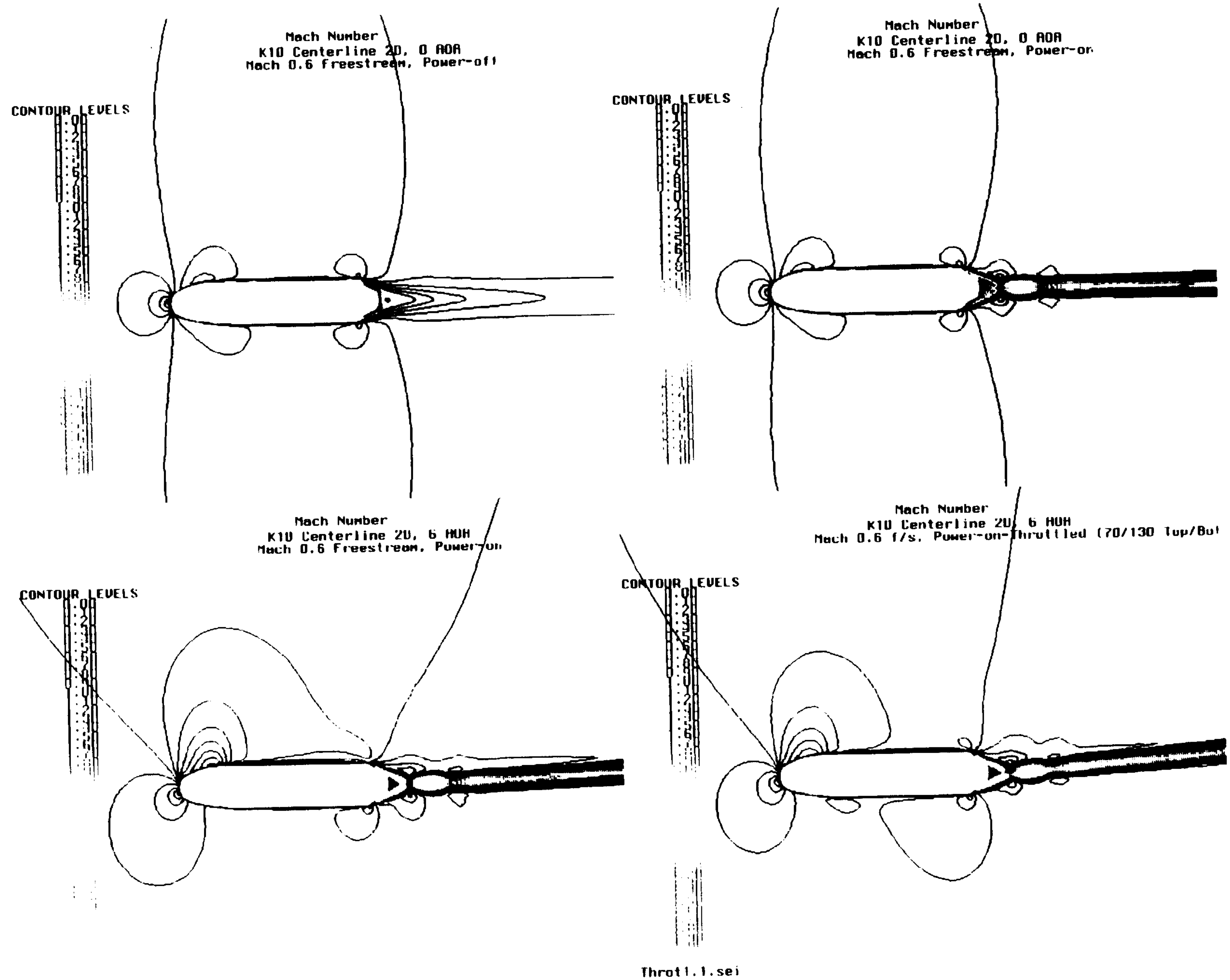

Mach Number
Mach 3.0 Freestream, 76Kft
K10 2D Centerline, 0 degrees Alpha
CONTOUR LEVELS
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00
2.20
2.40
2.60
2.80
3.00
3.20
3.40
3.60
3.80
4.00
4.20
4.40
4.60
4.80
5.00
5.20
5.40
5.60
5.80
6.00
6.20
6.40
6.60
6.80
7.00
q.1.img

K10 2D Centerline Pressure Coefficients




Mach 1.2 Alpha=0 degrees
power-off vs. power-on
Top, P-off
Bottom, P-off
Top, P-on
Bottom, P-on
Cp
X/L
aft end
Minor effect of plume is same on top and bottom of vehicle
Mach 1.2 Alpha=6 degrees
power-off vs. power-on
aft end
Slightly different effects between top and bottom of vehicle due to AOA.


Mach Number
Mach 0.6 Freestream, 12Kft
K10 Centerline 2D, 0 degree Alpha
CONTOUR LEVELS
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
1.30
1.40
1.50
1.60
1.70
1.80
1.90
2.00
2.10
2.20
2.30
2.40
2.50
2.60
2.70
2.80
2.90
3.00
3.10
3.20
3.30
3.40
3.50
3.60
3.70
3.80
q.1.img

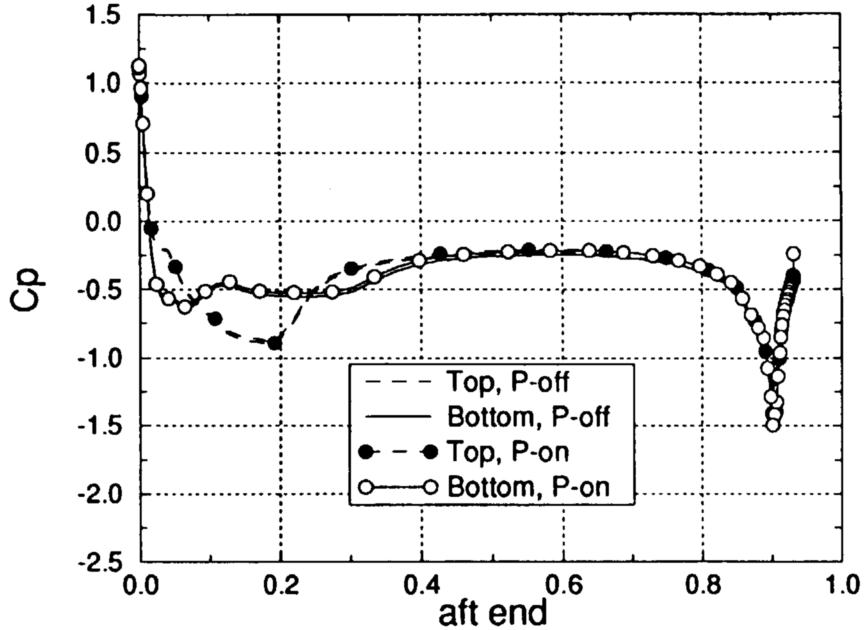


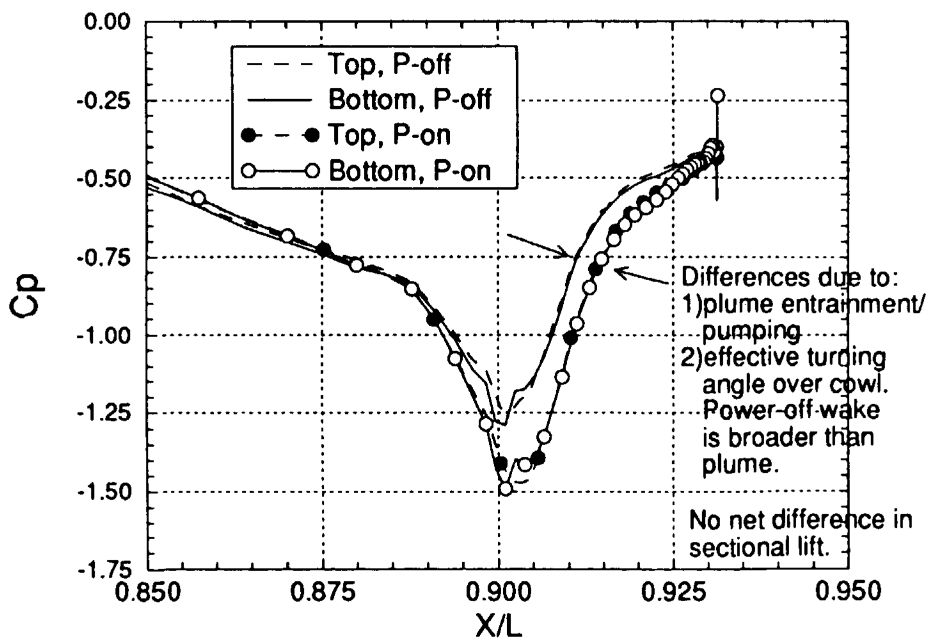
Mach Number
K10 Centerline 2D, 0 AOA
Mach 0.6 Freestream, Power-off
CONTOUR LEVELS
Mach Number
K10 Centerline 2D, 0 AOA
Mach 0.6 Freestream, Power-on
CONTOUR LEVELS
Mach Number
K10 Centerline 2D, 6 AOA
Mach 0.6 Freestream, Power-on
CONTOUR LEVELS
Mach Number
K10 Centerline 2D, 6 AOA
Mach 0.6 f/s, Power-on-Throttled (70/130 Top/Bot
CONTOUR LEVELS
Throt1.1.sei

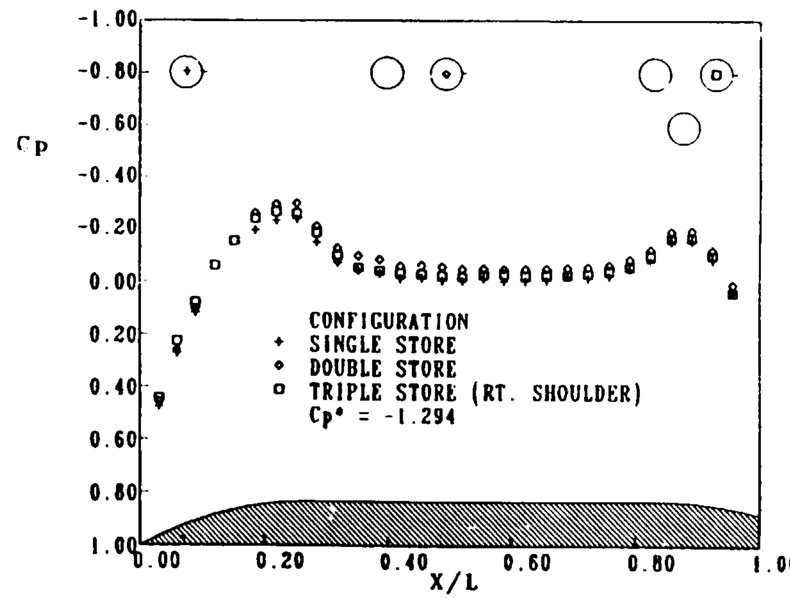
K10 2D Centerline Pressure Coefficient

Mach 0.6 Alpha=0 degrees

power-off vs. power-on



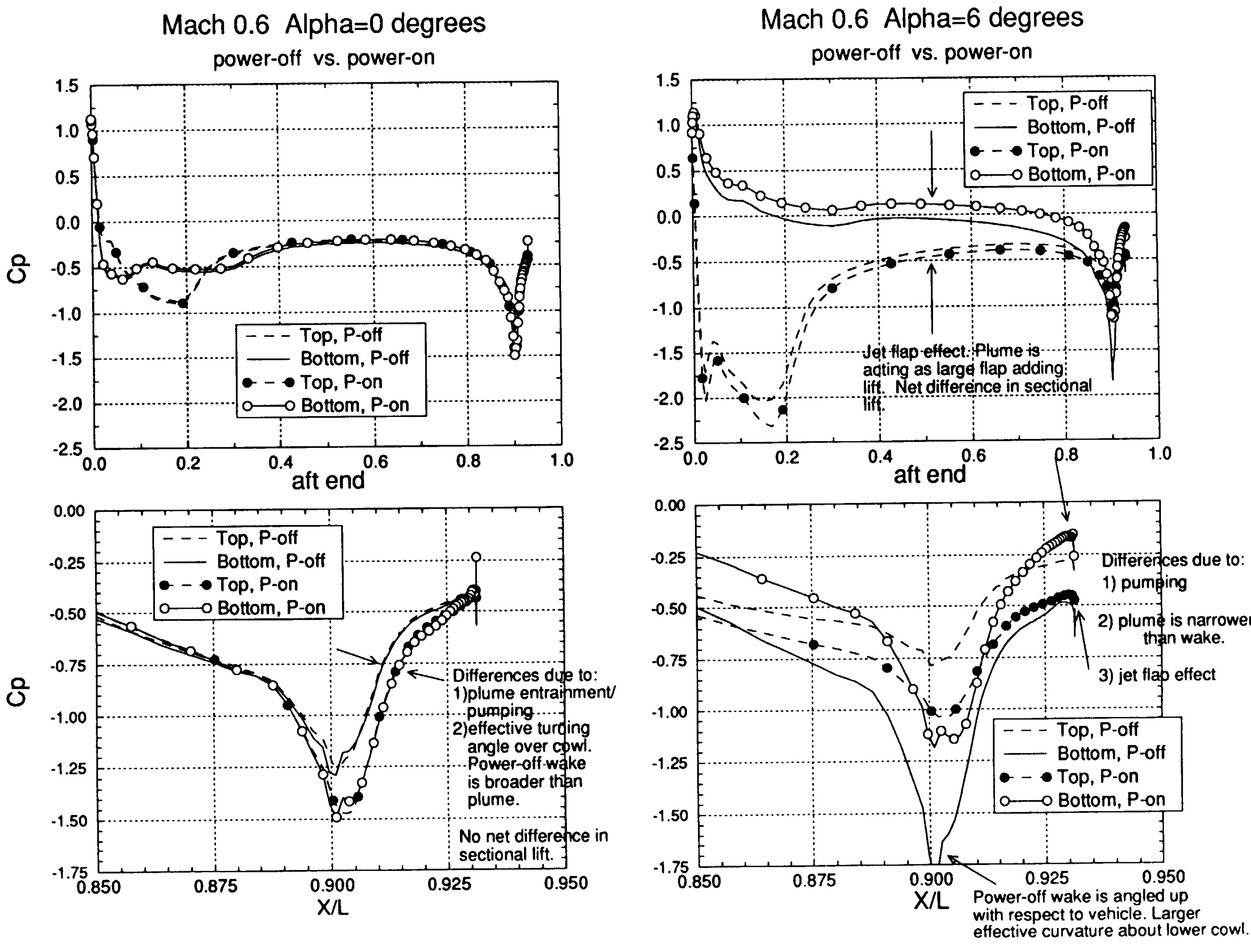




Mutual Interference Comparison,
M_∞ = 0.60, α = 0°, φ = 90°

Data from aircraft munition stores test, Cottrell, 1987.

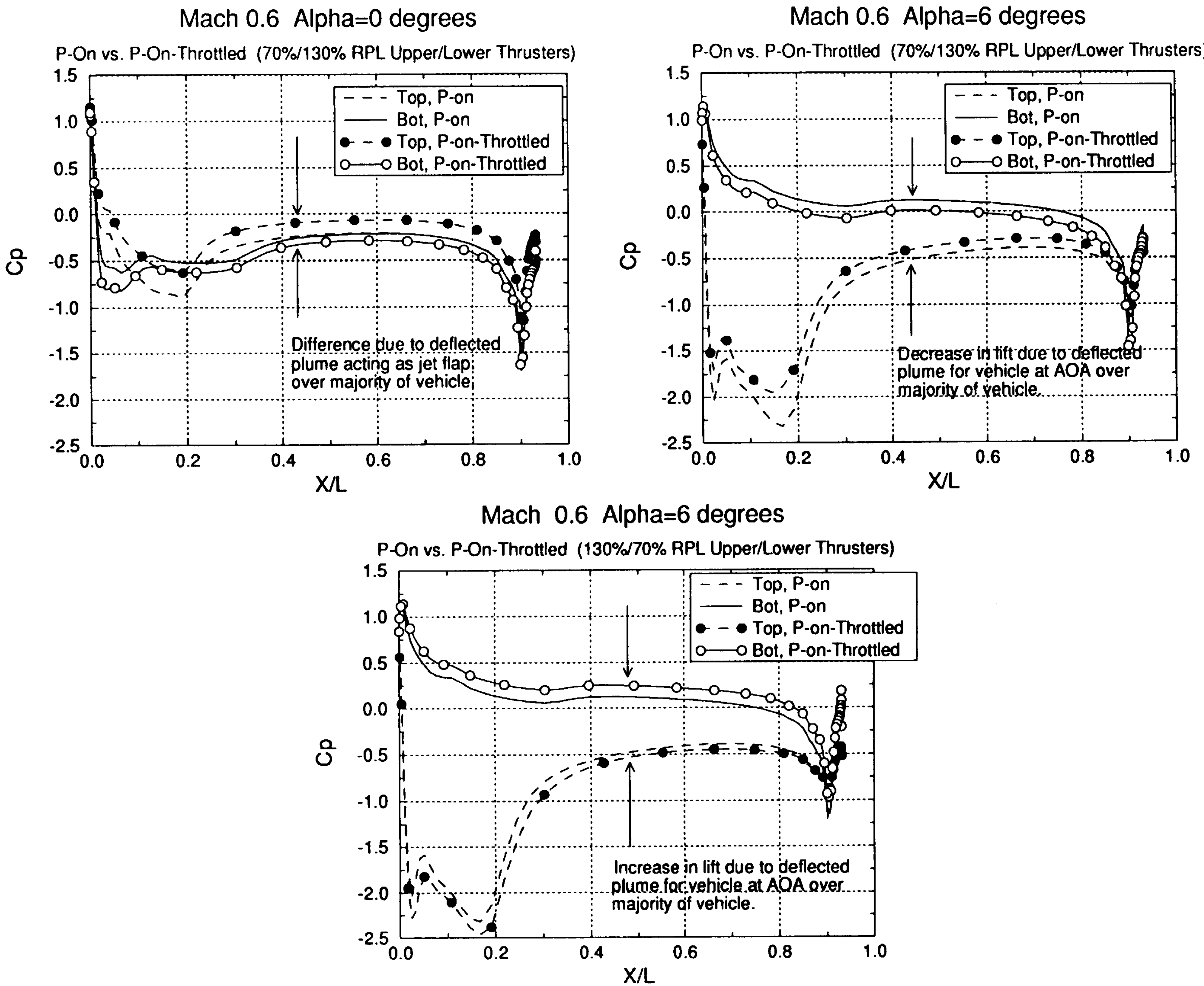
K10 2D Centerline Pressure Coefficient



CFD Results, cont.

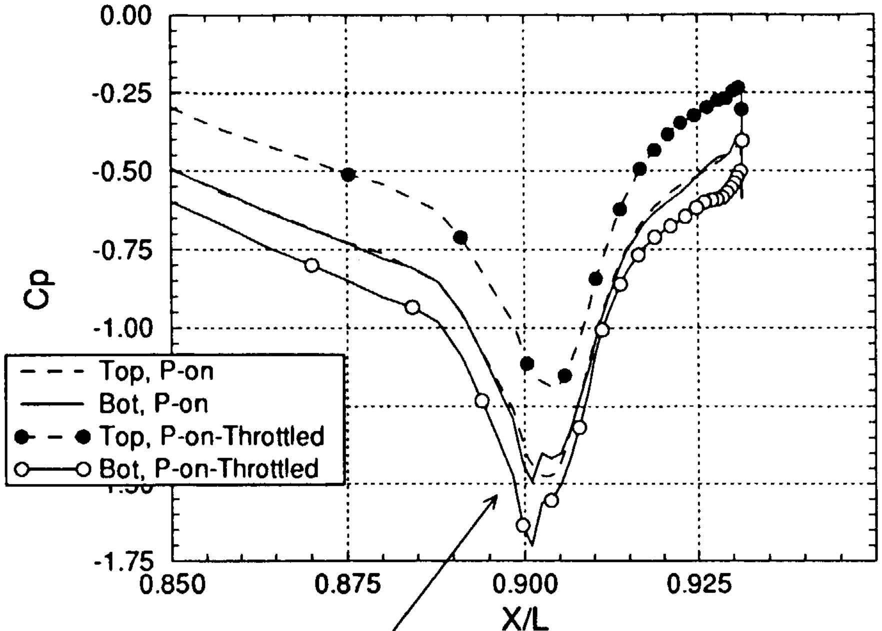
- **Mach 0.6 ~ 12Kft**
  - 0 degree α power-on vs. power-on-throttled
    - » Deflected plume effects lift consistently over length of vehicle through jet flap effect.
  - 6 degree α power-on vs. power-on-throttled
    - » Deflected plume effects lift differently on forward and aft part of vehicle through jet flap effect.

K10 2D Centerline Pressure Coefficients



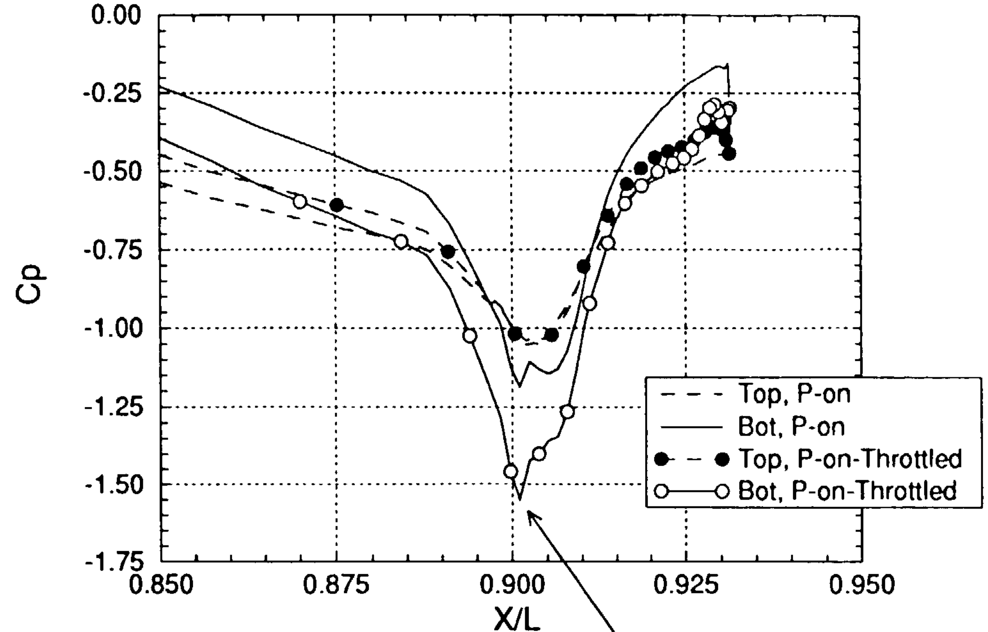
Mach 0.6 Alpha=0 degrees Aft End

P-On vs. P-On-Throttled (70%/130% RPL Upper/Lower Thrusters)



Mach 0.6 Alpha=6 degrees Aft End

P-On vs. P-On-Throttled (70%/130% RPL Upper/Lower Thrusters)

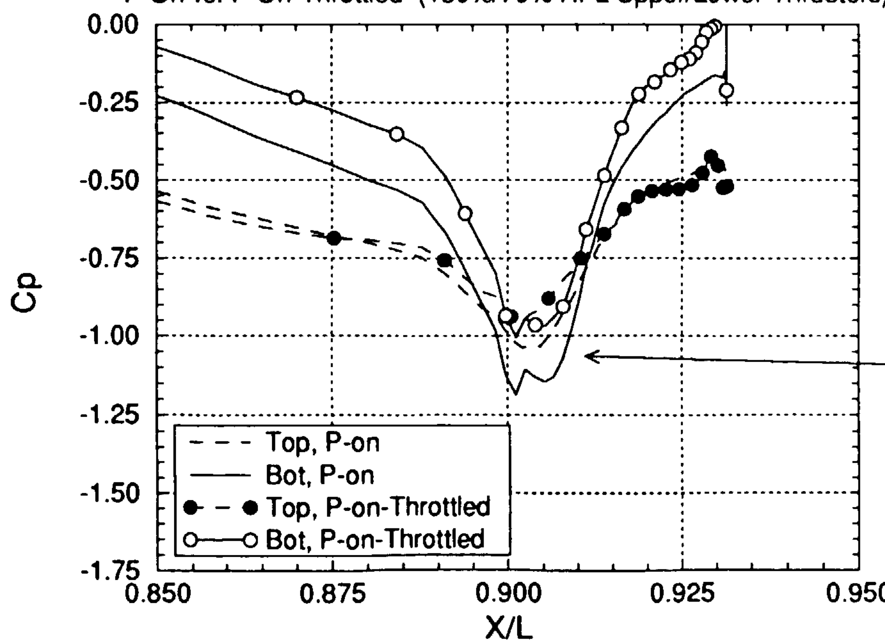


Plume deflection increases lift consistantly over entire vehicle.

Plume deflected up increases local negative lift on aft end.

Mach 0.6 Alpha=6 degrees Aft End

P-On vs. P-On-Throttled (130%/70% RPL Upper/Lower Thrusters)

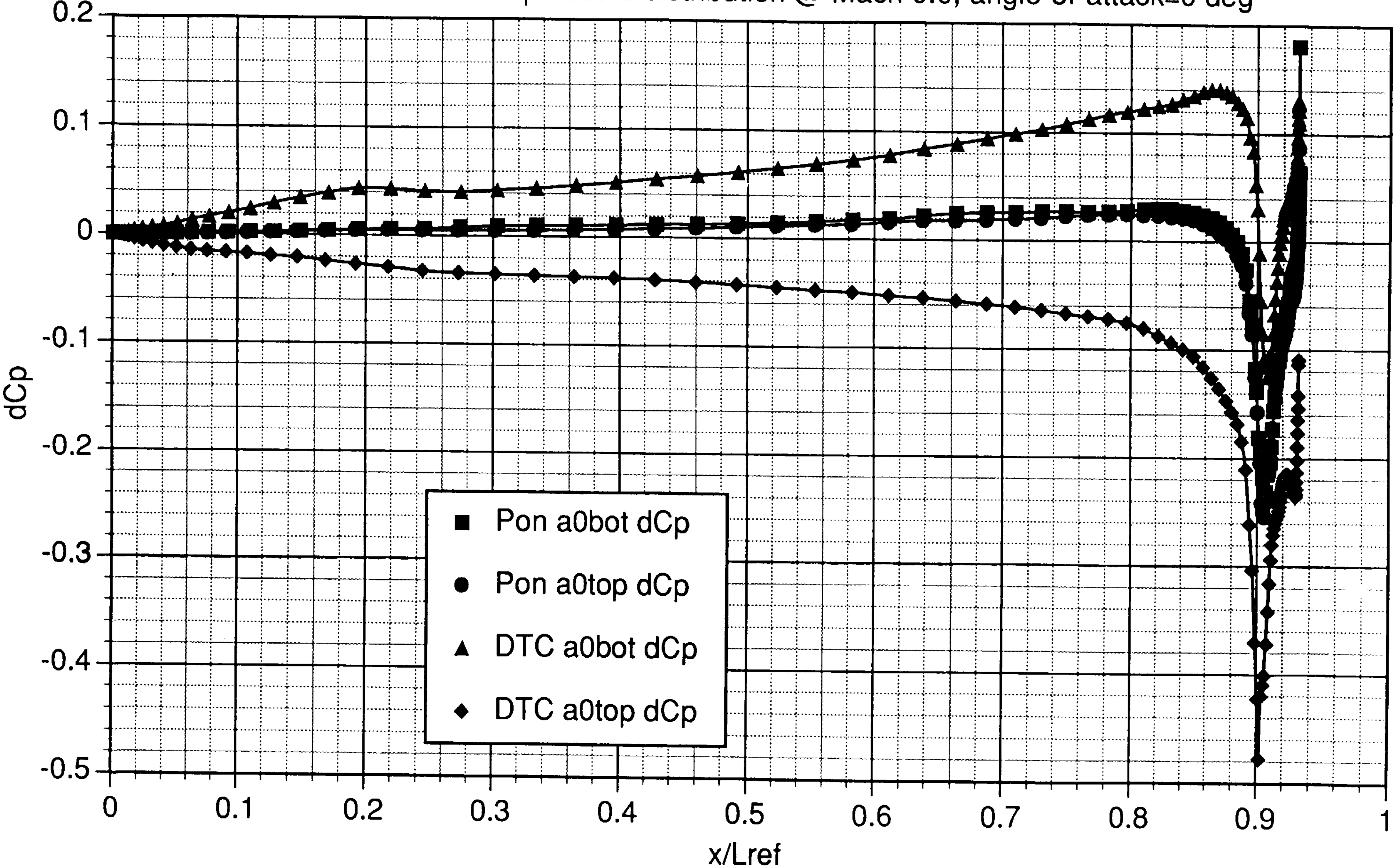


Plume deflected down decreases local negative lift on aft end.

Application of CFD to Preliminary Database

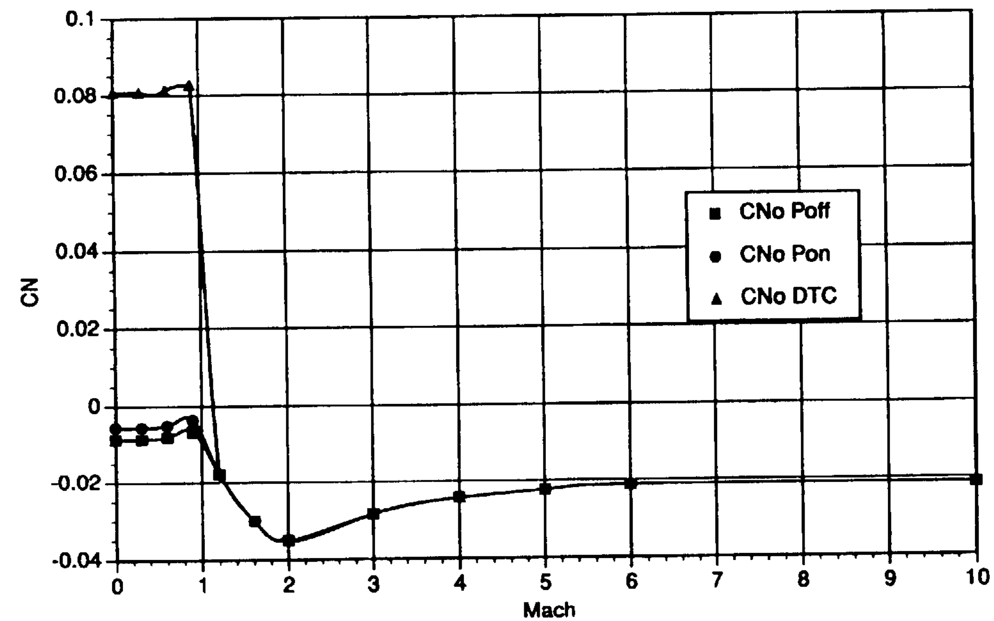
- **Increments were only generated for subsonic portion of aero database**
- **Pressure deltas were applied to database by assuming full effect at aft end and linearly decreasing to no effect at forward end of vehicle**

Plume effects on LB pressure distribution @ Mach 0.6, angle-of-attack=0 deg

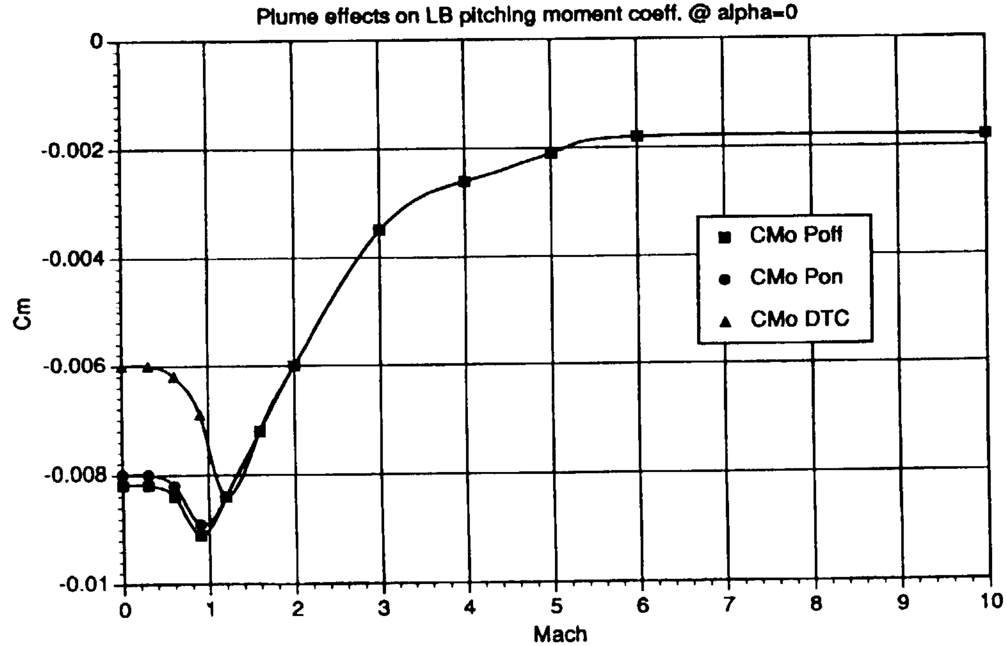


DTC - differential throttle control; upper/lower @ 130%/70%; Pon = 100%/100%
dCp = difference in pressure coefficient (power on - power off)

Plume effects on LB normal force coeff. @ alpha=0

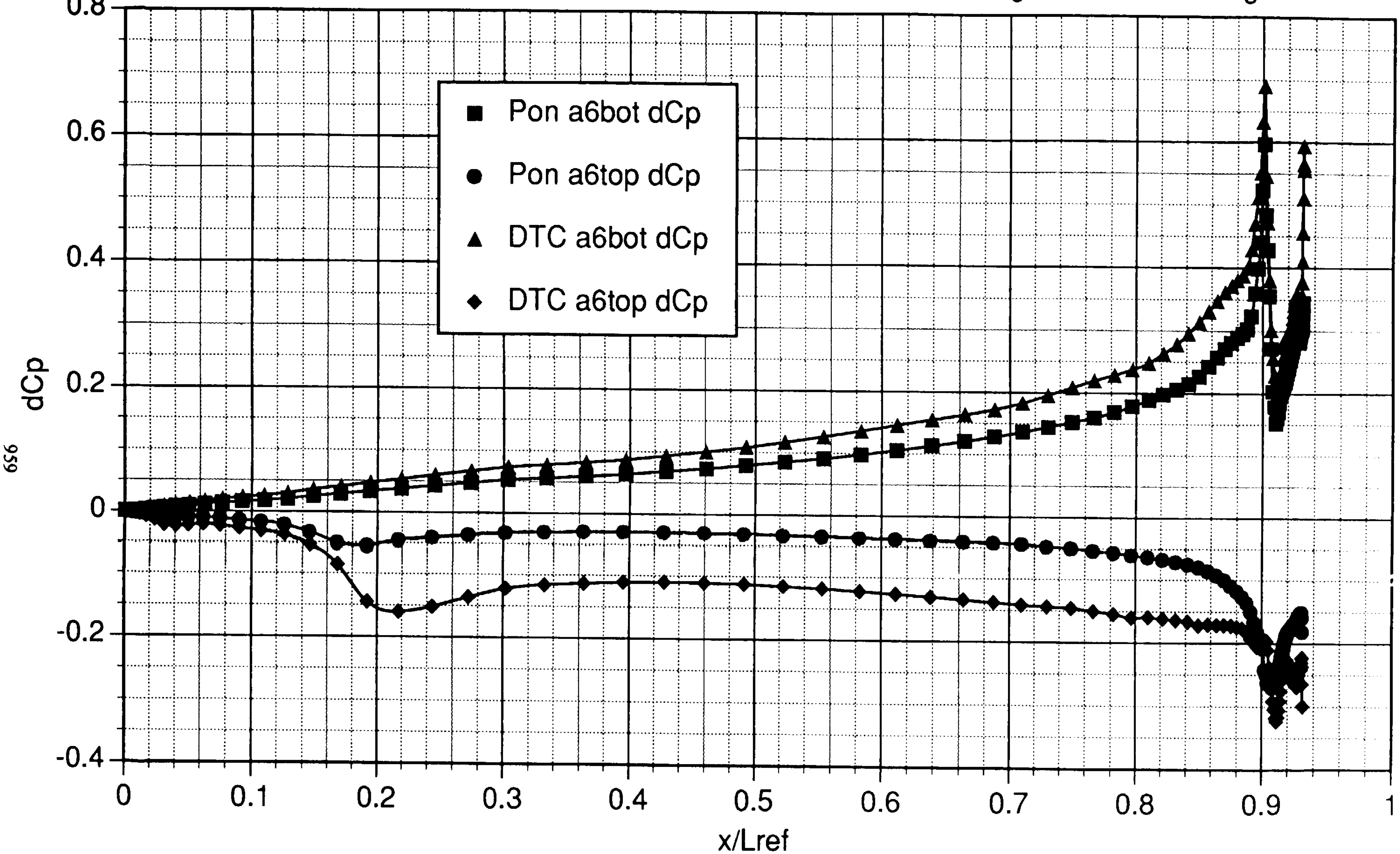


Plume effects on LB pitching moment coeff. @ alpha=0



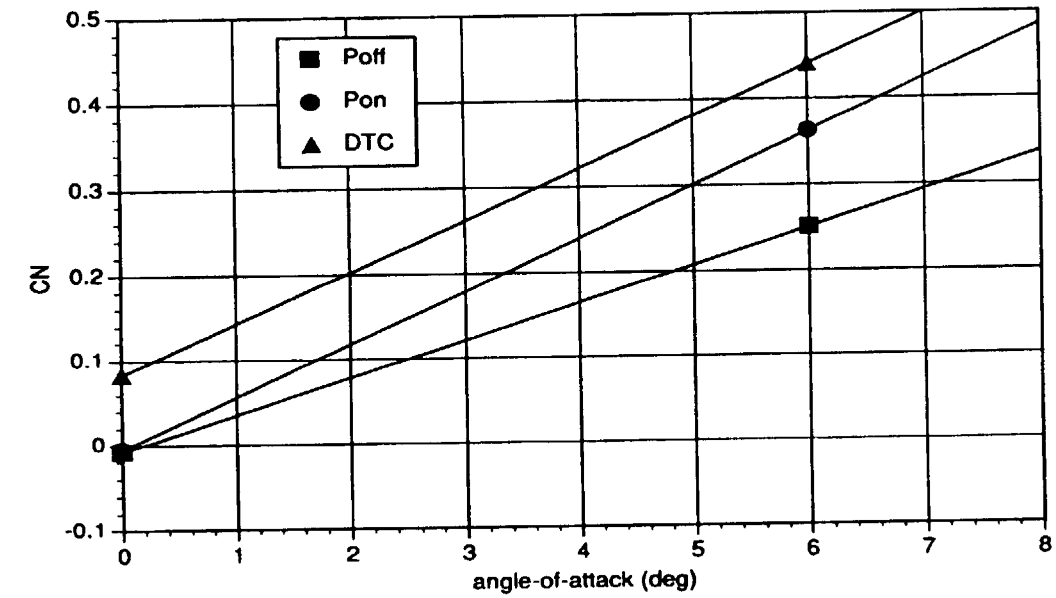
Sref=5600 sq ft; Lref=1450.0 in.; mom. ref. @ 72%.

Plume effects on LB pressure distribution @ Mach 0.6, angle-of-attack=6 deg

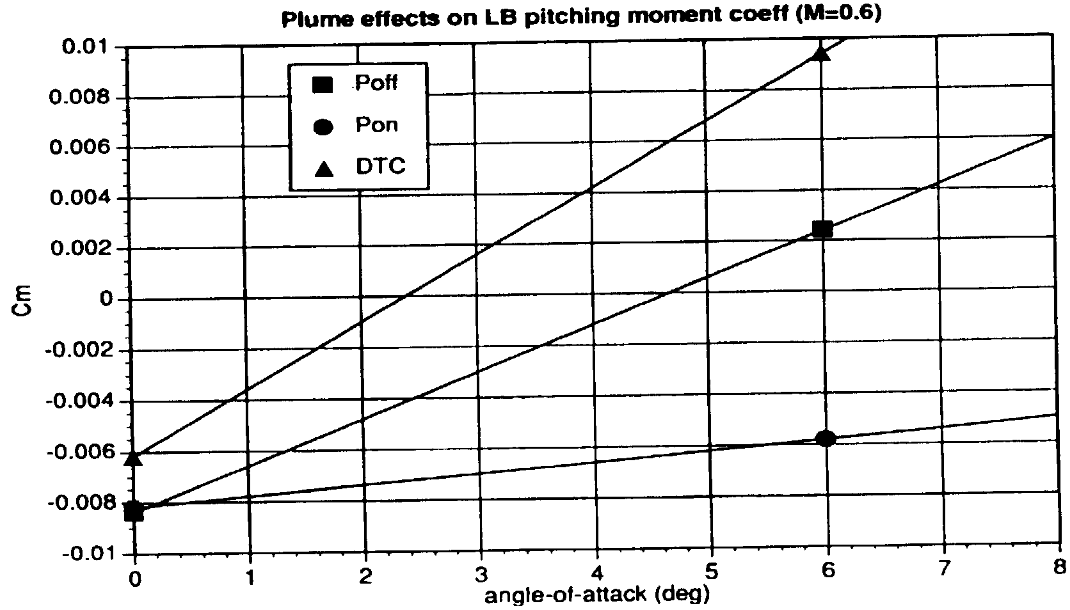


DTC - differential throttle control; upper/lower @ 130%/70%; Pon = 100%/100%
dCp = difference in pressure coefficient (power on - power off)

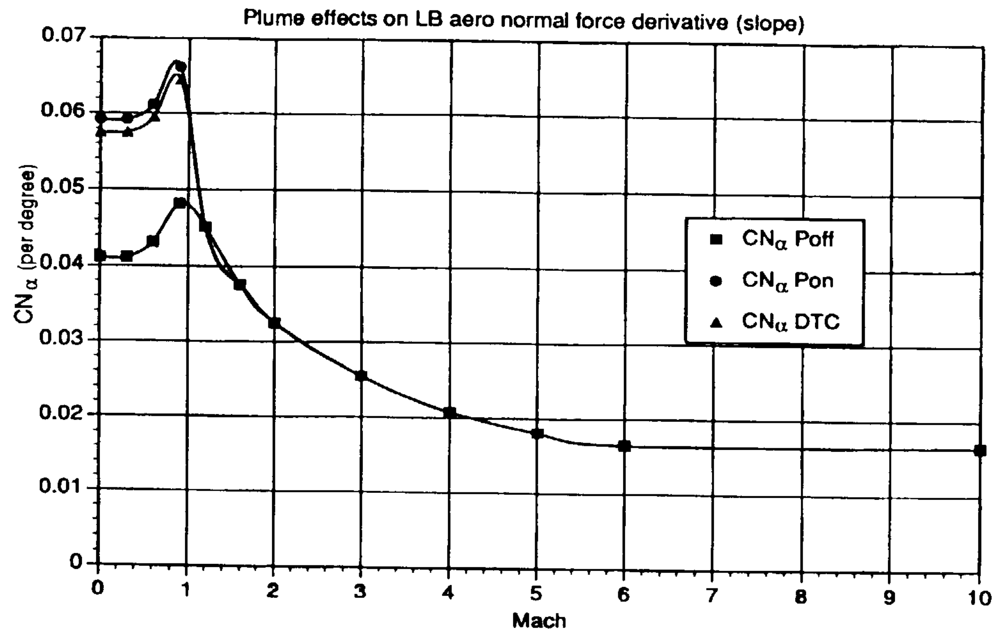
Plume effects on LB normal force coeff (M=0.6)

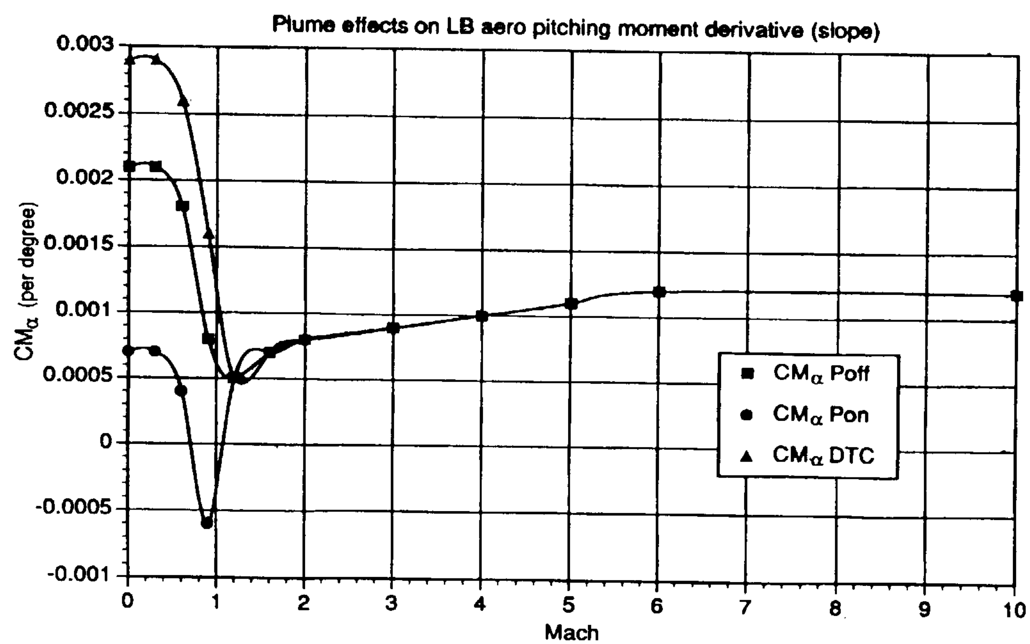


Plume effects on LB pitching moment coeff (M=0.6)



Sref=5600 sq ft; Lref=1450.0 in.; mom. ref. @ 72%.





Sref=5600 sq ft; Lref=1450.0 in.; mom. ref. @ 72%.

Conclusions

- **No significant plume aerodynamic effects existed for supersonic flight regime. Plume induced separation of flow over vehicle was not a significant effect on aerodynamics of K10.**
- **No significant plume effects seen between power-on and power-off at 0 degree α for Mach numbers analyzed.**
- **Significant plume/external flow interactions existed for Mach 0.6 at angles of attack through jet flap effect, jet entrainment and change in effective cowl angle.**
  - Jet flap effect propagated well forward in 2D analysis.
  - Jet entrainment and increased/decreased effective cowl angle affected the aft end of K10.
- **3D calculations are under way. Initial results indicates less plume effect on the forward part of vehicle than in 2D analysis.**
- **A methodology has been developed to generate first order plume effect increments for a power-off aerodynamic database using 2D centerline CFD analysis.**