Rapid Euler CFD For High-Performance Aircraft Design

Final Report
NASA Langley Research Center
Contract NAS1-96014

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Outline

- Motivation
- Configuration
- Resources
- Metrics
- Results
- Falling Leaf
- Discussion
- Future Efforts

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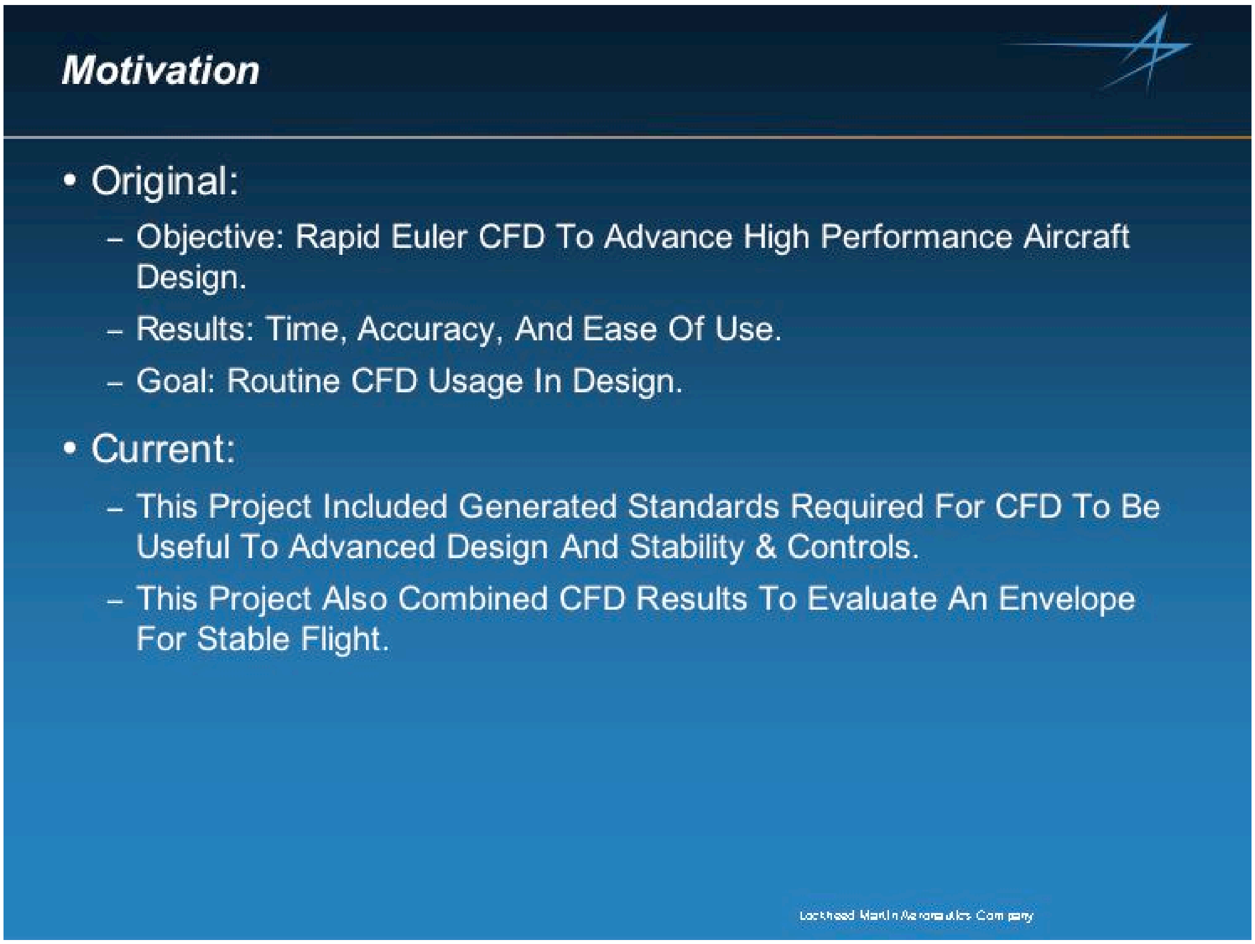
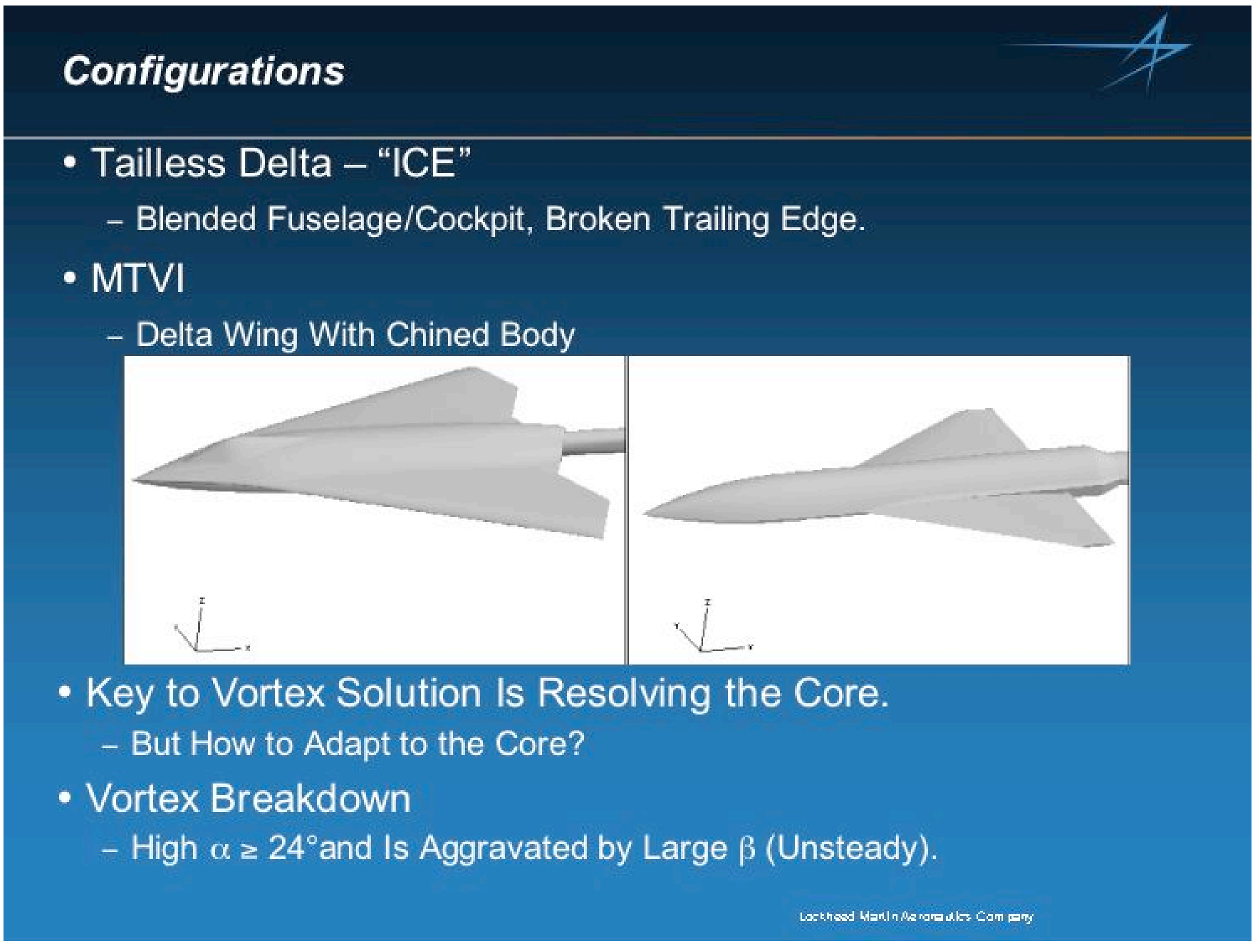
The goal here was to present one approach to rapid CFD for S&C using an unstructured inviscid method, in order to eventually assess S&C properties as early in the design process as possible. Specific results are presented regarding time, accuracy (as compared to a baseline wind tunnel database) and simplicity for the user. For COMSAC, it's more important to talk about the "specifications" required by Advanced Design and S&C, as well as how the CFD results can be combined for envelope evaluation.



Two configurations were considered, the tailless delta wing ("ICE") configuration and the MTVI configuration. Each configuration actually has two vortices, with the second vortex on the ICE model starting at the change in camber and thickness where the fuselage and the wing blend. Accurate CFD analysis on vortex-dominated flows requires resolving the vortex core; adaptive methods can focus in on the core, but may need to be setup to do so. Vortex breakdown will also be significant in a vortex-dominated flow.



Many CFD cases were run on the two configurations to complete the run matrices.

Run Matrix

MTVI, α-Sweep, Inviscid									
β	α								
0		12		20		30		40	
2	6	12	16	20	25	30	35	40	45

Tailless Delta, α-Sweep, Inviscid										
β	α									
0	0		10	15	20					30
5	0		10	15	20					30
10	0	5	10	15	20	22	24	26	28	30
20	0	5	10	15	20	22	24	26	28	30

Tailless Delta, β-Sweep, Inviscid								
α	β							
20	2.5	5.0	7.5	10.0	12.5	15.0	17.5	20.0

Tailless Delta, Viscous			
β	α		
10	22	24	28
20	22		28

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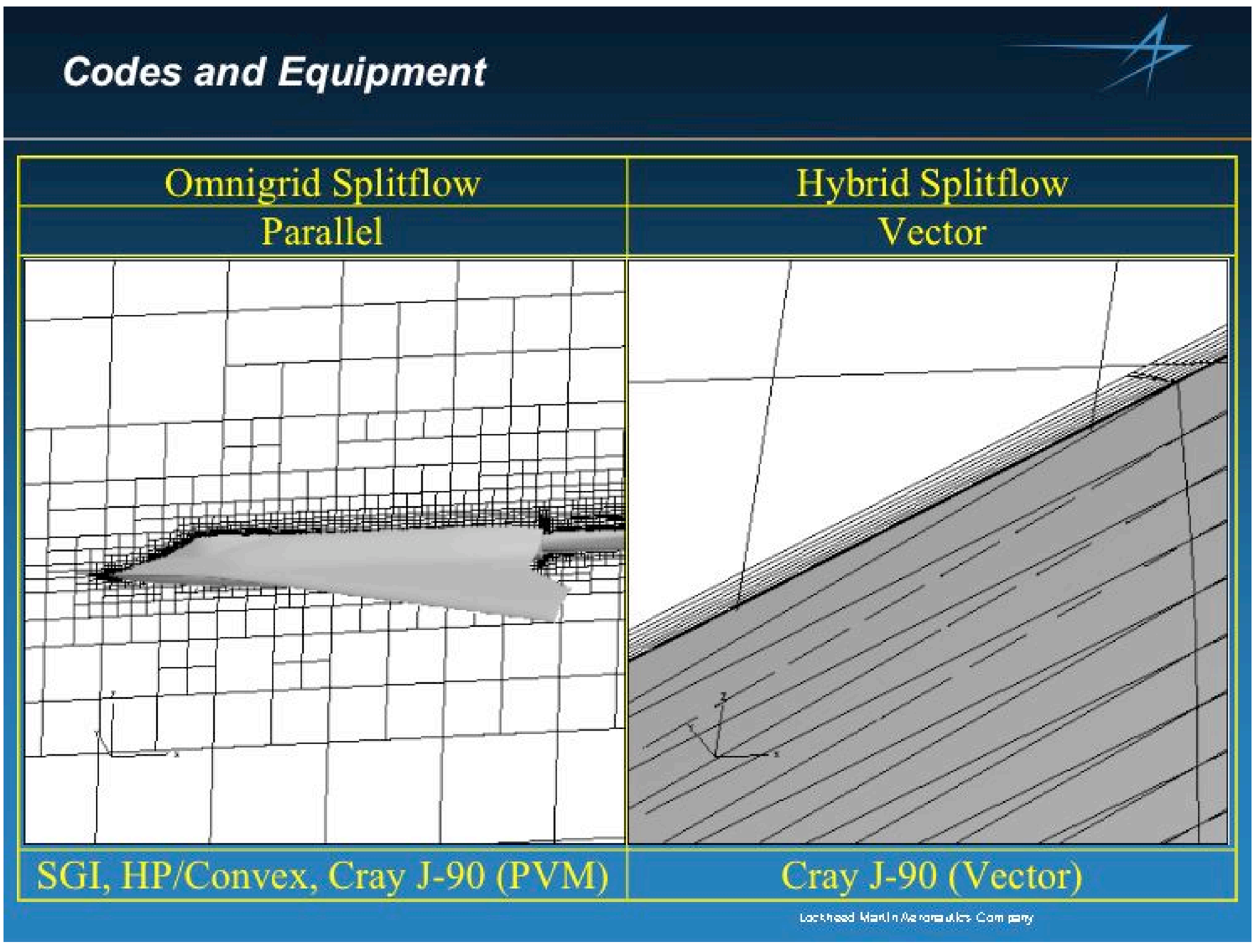
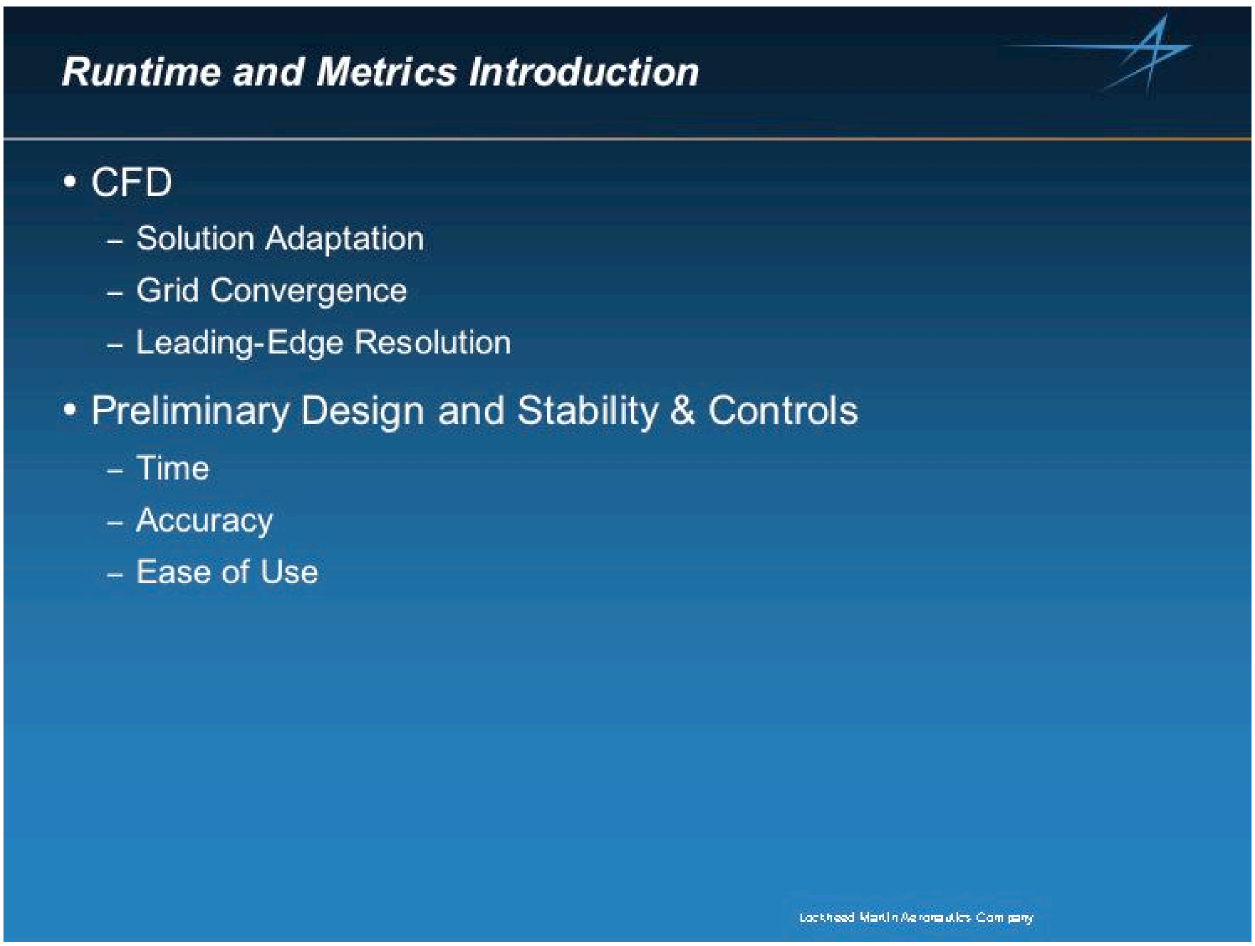
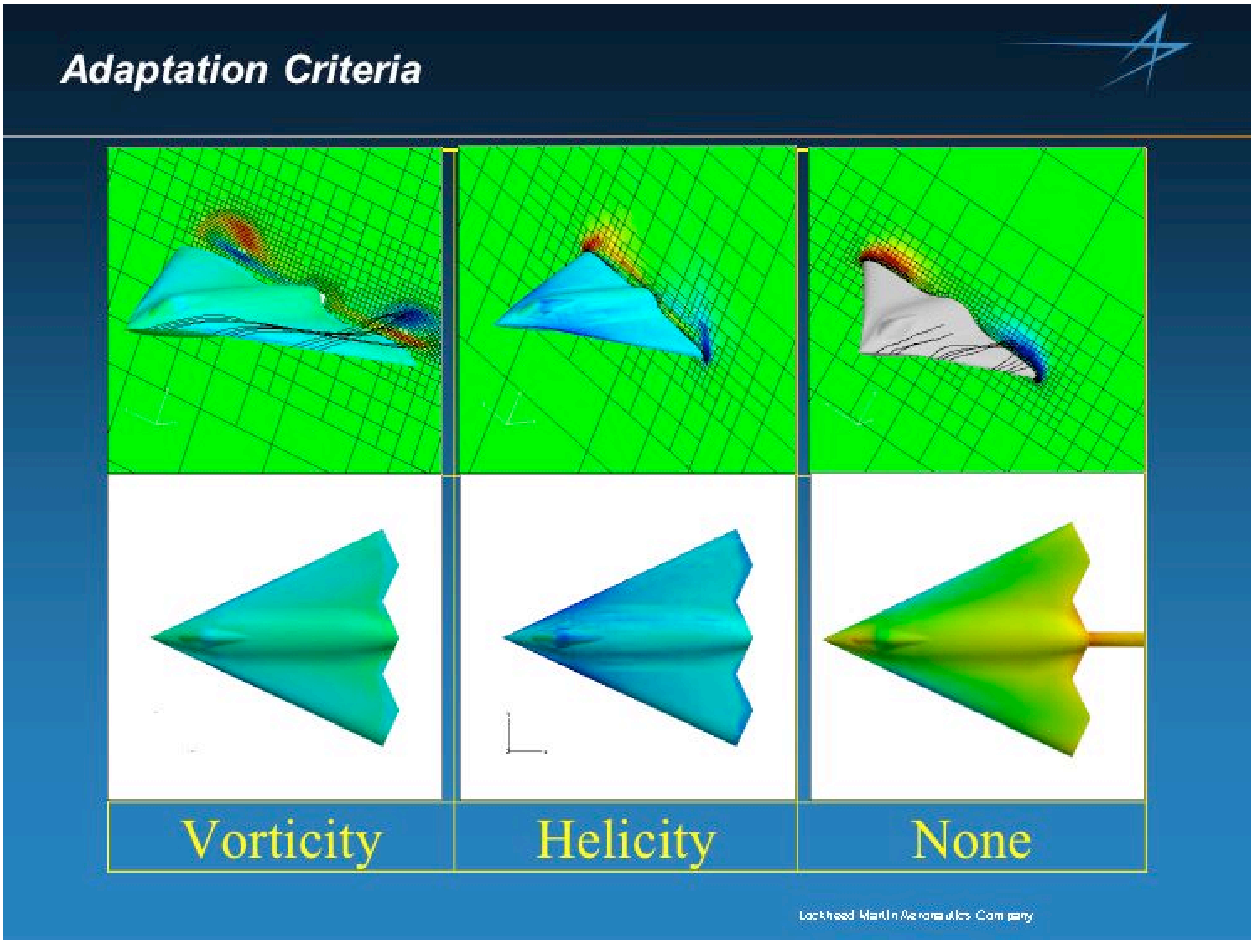
Two versions of Splitflow were used; the parallel version does not support the hybrid grids made from prisms extruded from the surface triangulation. The parallel version is still used today on engineering workstations, SGI Origins, and parallel clusters.



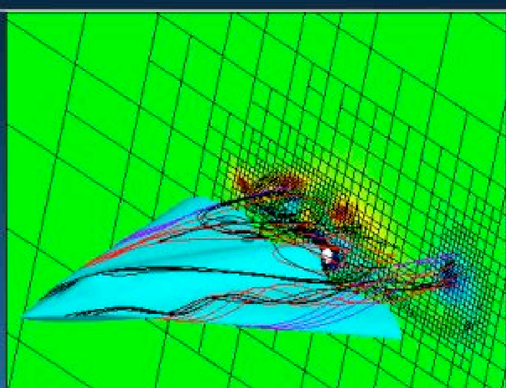
The contract effort was divided into two parts, CFD analysis and metrics. The CFD analysis used solution-based adaptation, checked for grid convergence as part of the data comparison, and considered grid resolution as part of the study. Metrics were specified by representatives from two groups, Preliminary Design and Stability & Controls, for the time required, accuracy required, and some measure of the ease of use.

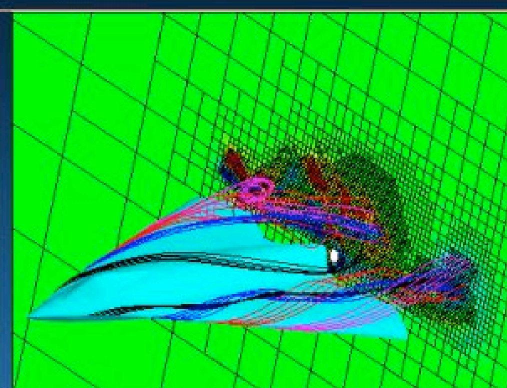


"You cannot solve what you do not resolve."—Steve Karman. Solution-based grid adaptation gives the grid the opportunity to adapt to the flow solution as the solution progresses. The grid itself helps set what kinds of flow solutions can be modeled, so it is critical to have an appropriate grid. The three plots here show an example of adapting to vorticity, helicity, or not at all, and they show dramatically different results. Traditionally, helicity was used by Splitflow to adapt on vortical structures—the concern was that vorticity would simply add cells to the boundary layer. Unfortunately, helicity does not highlight the vortex core, which is critical for modeling a vortex, and the field value of helicity itself fall to near-noise levels after a vortex burst. Together, those effects make considering raw vorticity critical to adapting to vortex-dominated flowfields.



Tailless Delta wing, Grid Convergence





- 400K Cells 800K Cells
- A Few Cases Grid-converged At 400K And 700K+ Cells.
- No Noticeable Improvement Found In Matching WT Data With The Larger Grid (Any Useful Euler Data Can Be Found At 400K Cells).
- Results Suggest That 400K Cells May Be A Minimum, Due To Necessary Resolution Of The Vortex Core Off The Surface.

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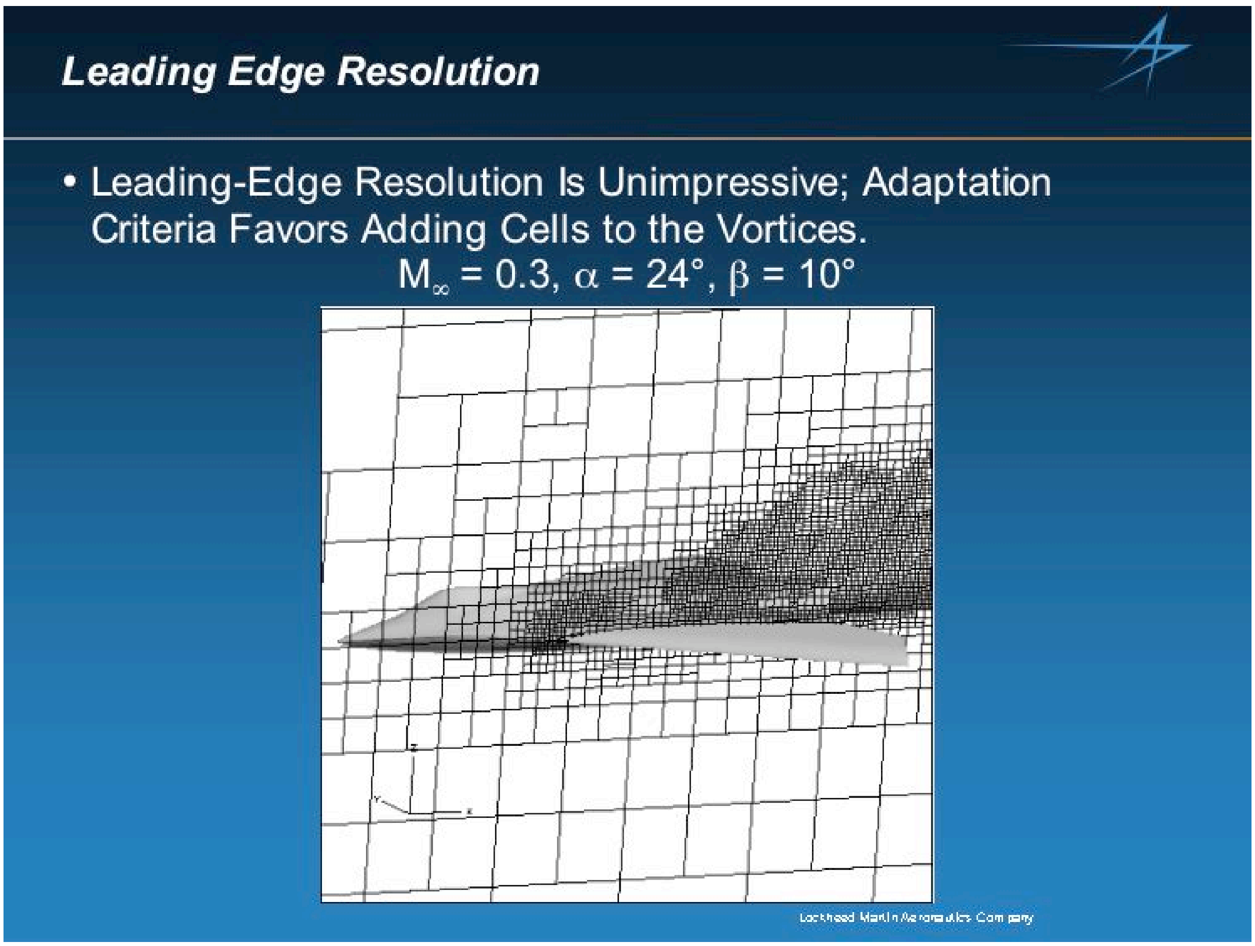
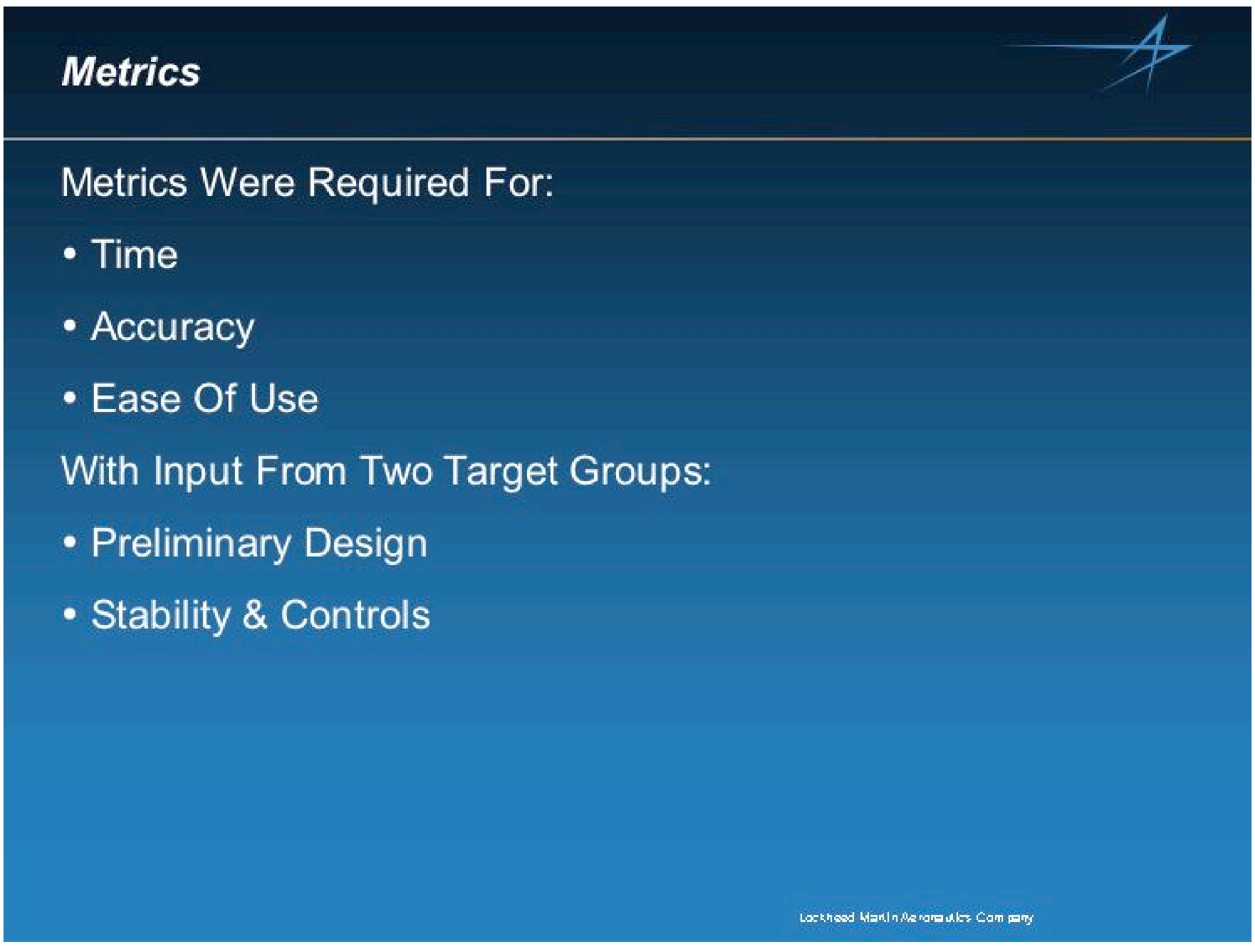
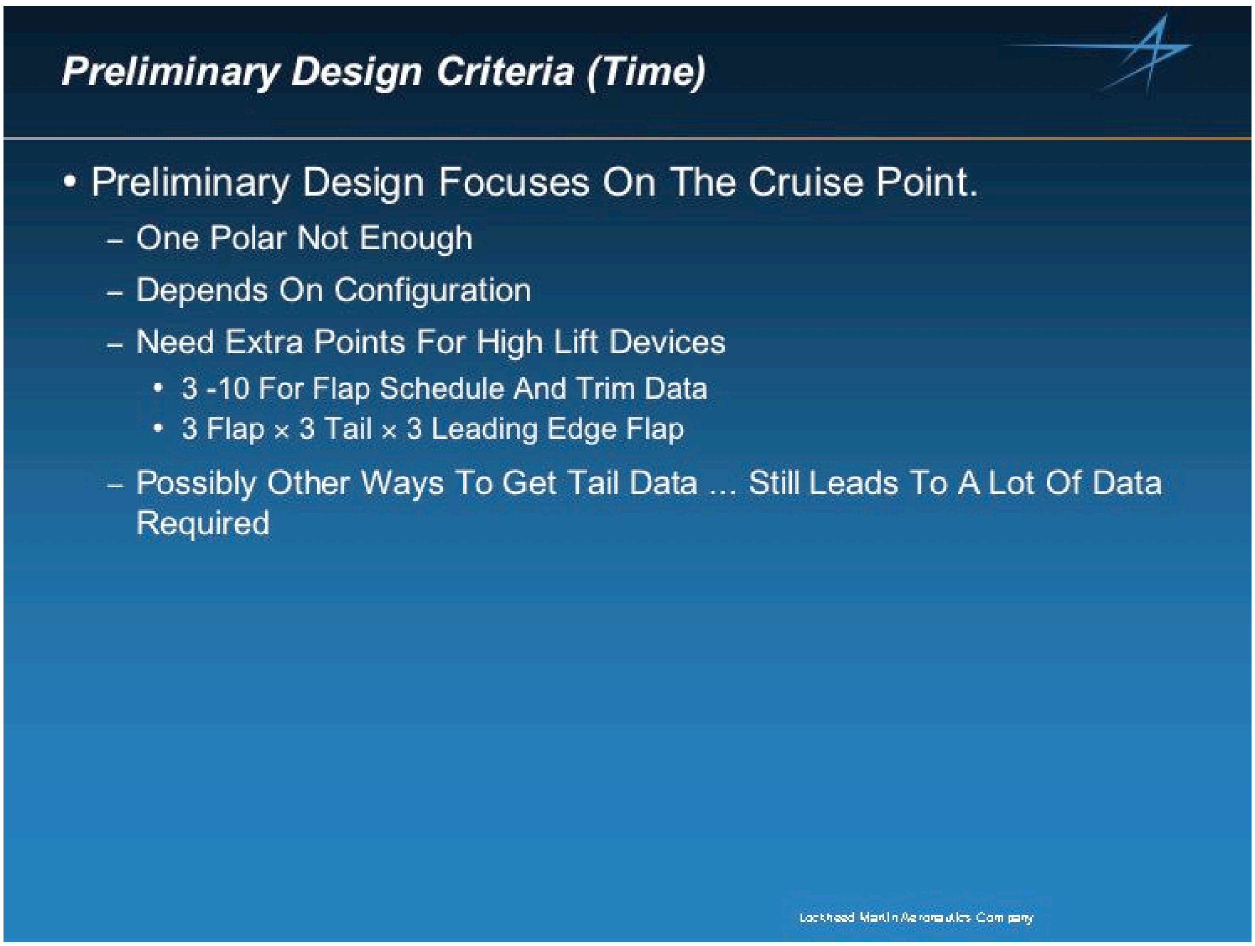
Sufficient leading-edge resolution is often critical to setting up the proper flowfield and accurately computing the aerodynamic characteristics on the suction-side of the vehicle. However, the gradients of classic analyzed variables (e.g. pressure, Mach number, density) are not very large compared to those inside of vortices or near shocks. This results in most of the solution-based adaptation going into those areas, not to the leading edge.



Metrics are one of the real topics of discussion here. Metrics were developed by consulting with specific colleagues in the areas of Advanced Design and Stability & Control. The metrics presented here could be considered a start for a discussion of more general standards.



Criteria for evaluating CFD for Preliminary Design were produced by discussions with individuals involved in Preliminary Design. At this point, the data presented only represents a few opinions on the matter, but it's a start.



Preliminary Design Criteria (Time) (continued)

- Current Approximate Methods (1998) Require About One Week to Do One Aerodynamic Analysis.
  - The Codes Are Fast
  - Most of the Time Is Spent on Setup, Calibration, and Analysis
- Aerodynamics Wants a Full Matrix in 24 Hours
  - So Need One α Sweep Per Hour

At This Point, CFD Would Become the Preliminary Aerodynamic Design Tool

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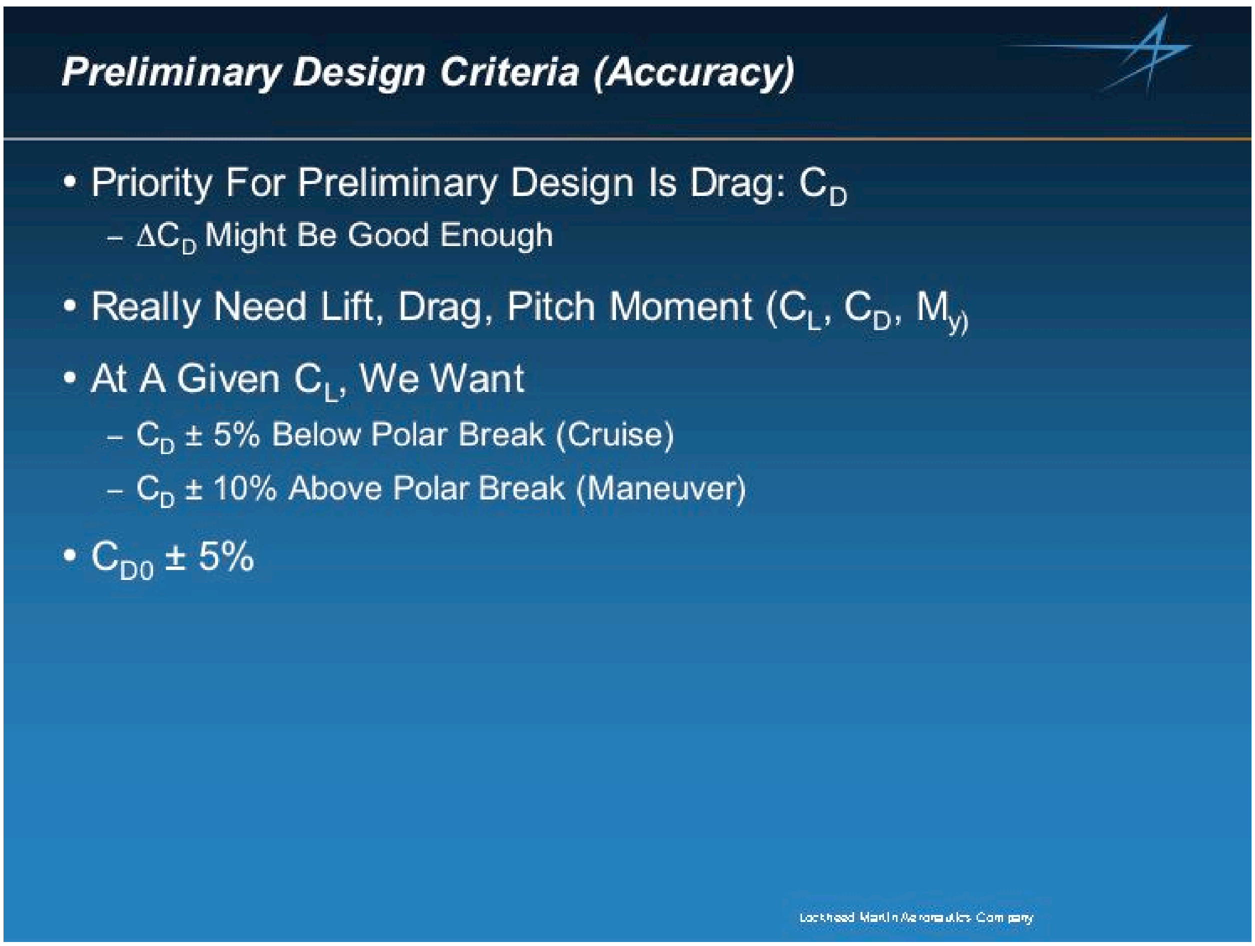
Preliminary design is focused on generating the necessary lift at the minimum drag.



Preliminary Design Criteria (Ease of Use)

- CFD Tools Often Require Many Training Hours
  - Documentation May Not Be Clear
- CFD Tools Often Have Too Many Parameters To Tweak
  - But Not Enough Parameters To Control the Solution?
- Need Parameter Sets That Work Consistently For A Given Class Of Problem
  - Prefer More Automated Analysis
- A GUI Would Be Nice
  - Perhaps An Expert-Type Input Checker With A Model To Help Set Parameters

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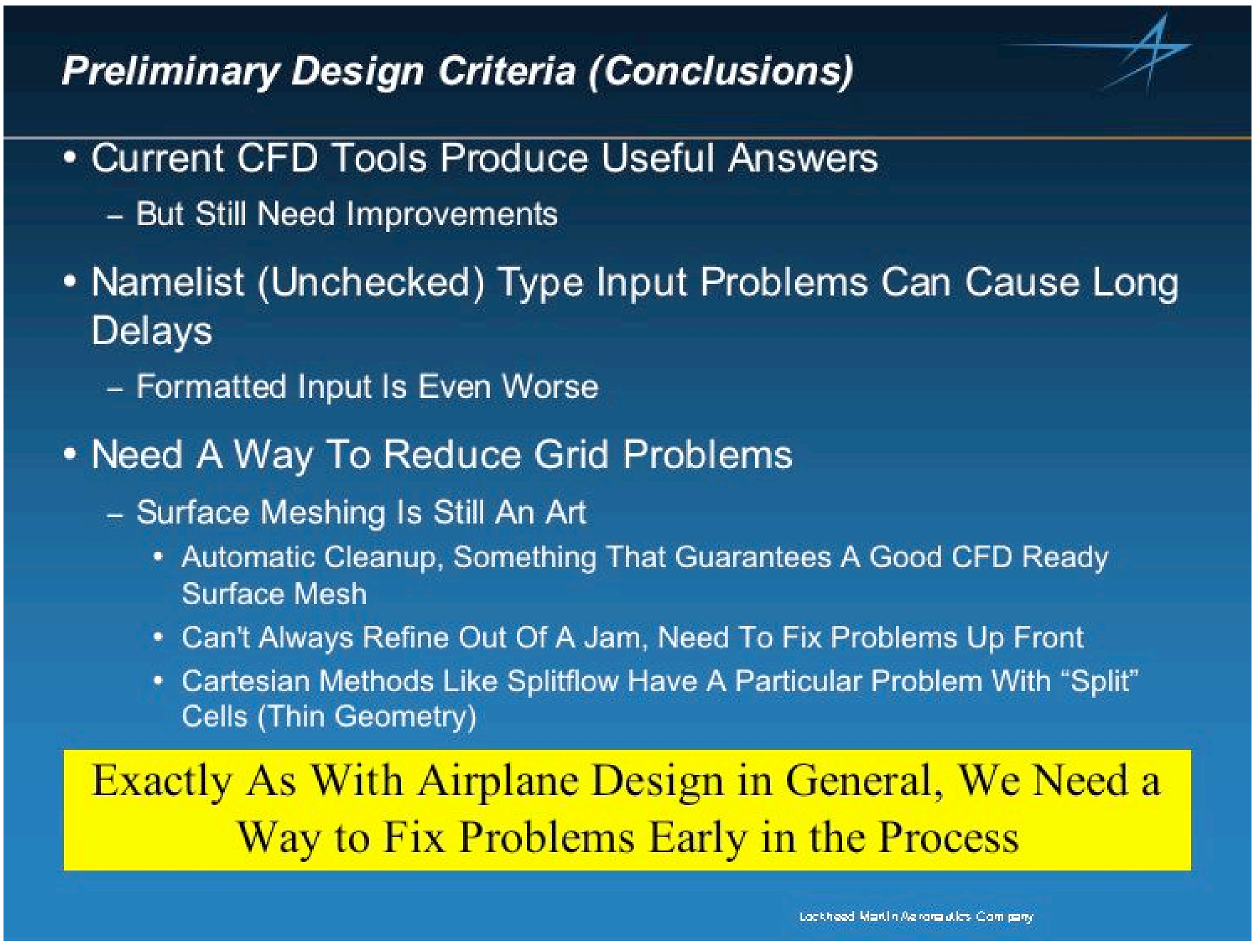
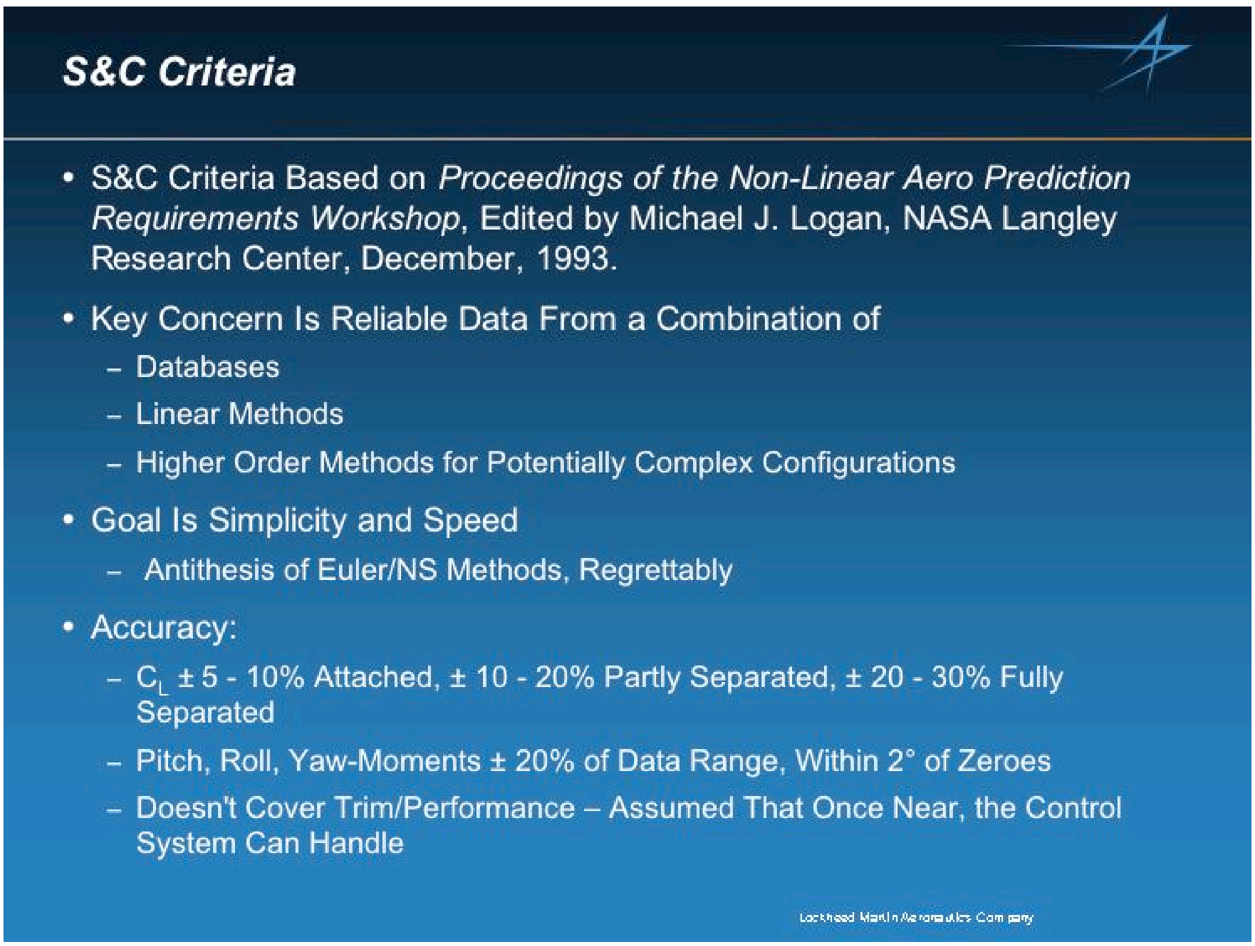
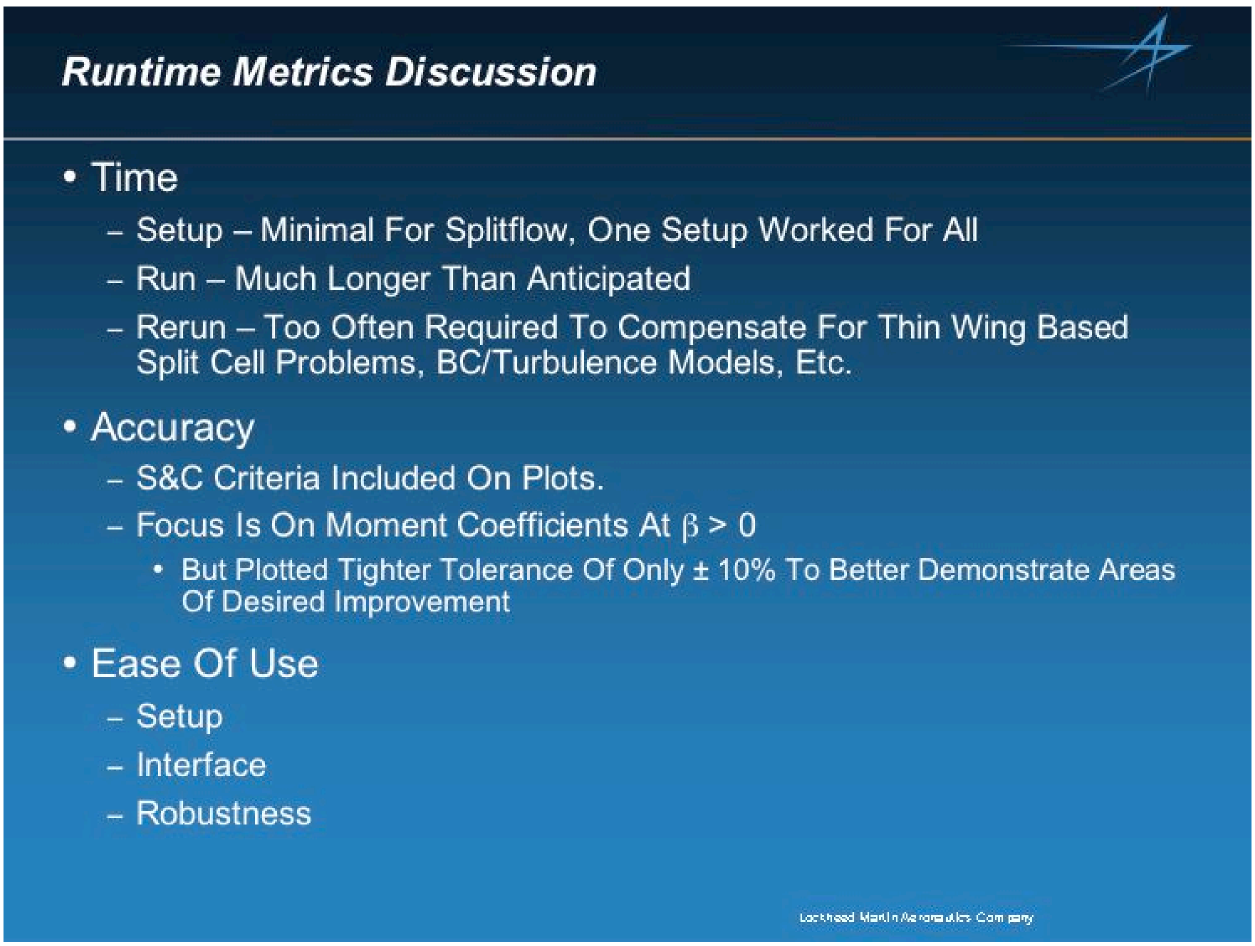
CFD tools are very useful already, but there are still needed improvements. The user interface is the weak spot, both in getting control information into the code, and in getting configuration information in. These weaknesses affect other codes, too, not just Splitflow, which is very dependent on a "good" surface mesh.



S&C requirements are a little different than Advanced Design, which really focuses on performance. The really tough one is the "within two degrees of zeroes." When plotted, that band really necks down, and when evaluated, it's very difficult to accomplish with the methods in this presentation.




Runtime Metrics Discussion
• Time
– Setup – Minimal For Splitflow, One Setup Worked For All
– Run – Much Longer Than Anticipated
– Rerun – Too Often Required To Compensate For Thin Wing Based Split Cell Problems, BC/Turbulence Models, Etc.
• Accuracy
– S&C Criteria Included On Plots.
– Focus Is On Moment Coefficients At $\beta > 0$
• But Plotted Tighter Tolerance Of Only ± 10% To Better Demonstrate Areas Of Desired Improvement
• Ease Of Use
– Setup
– Interface
– Robustness
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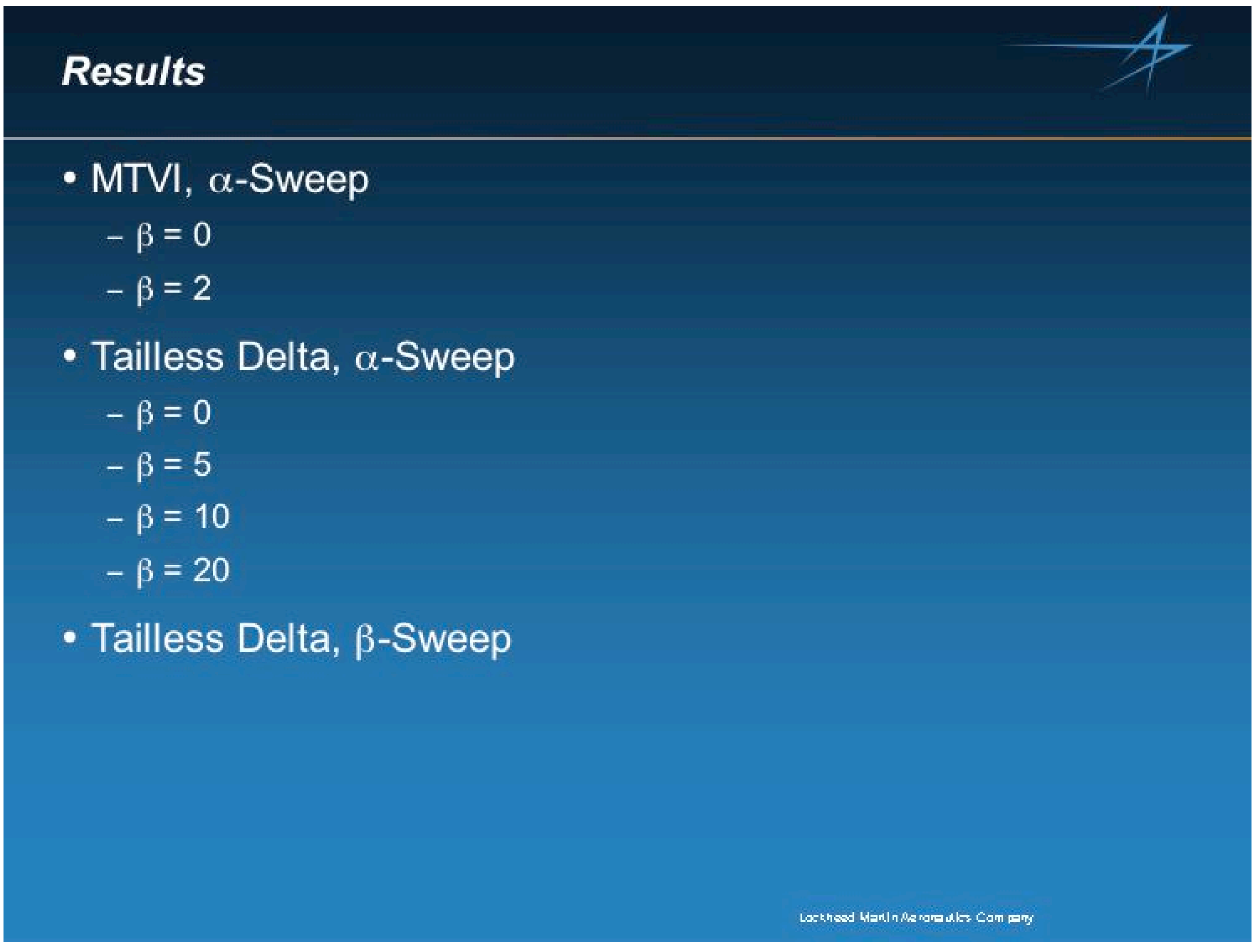
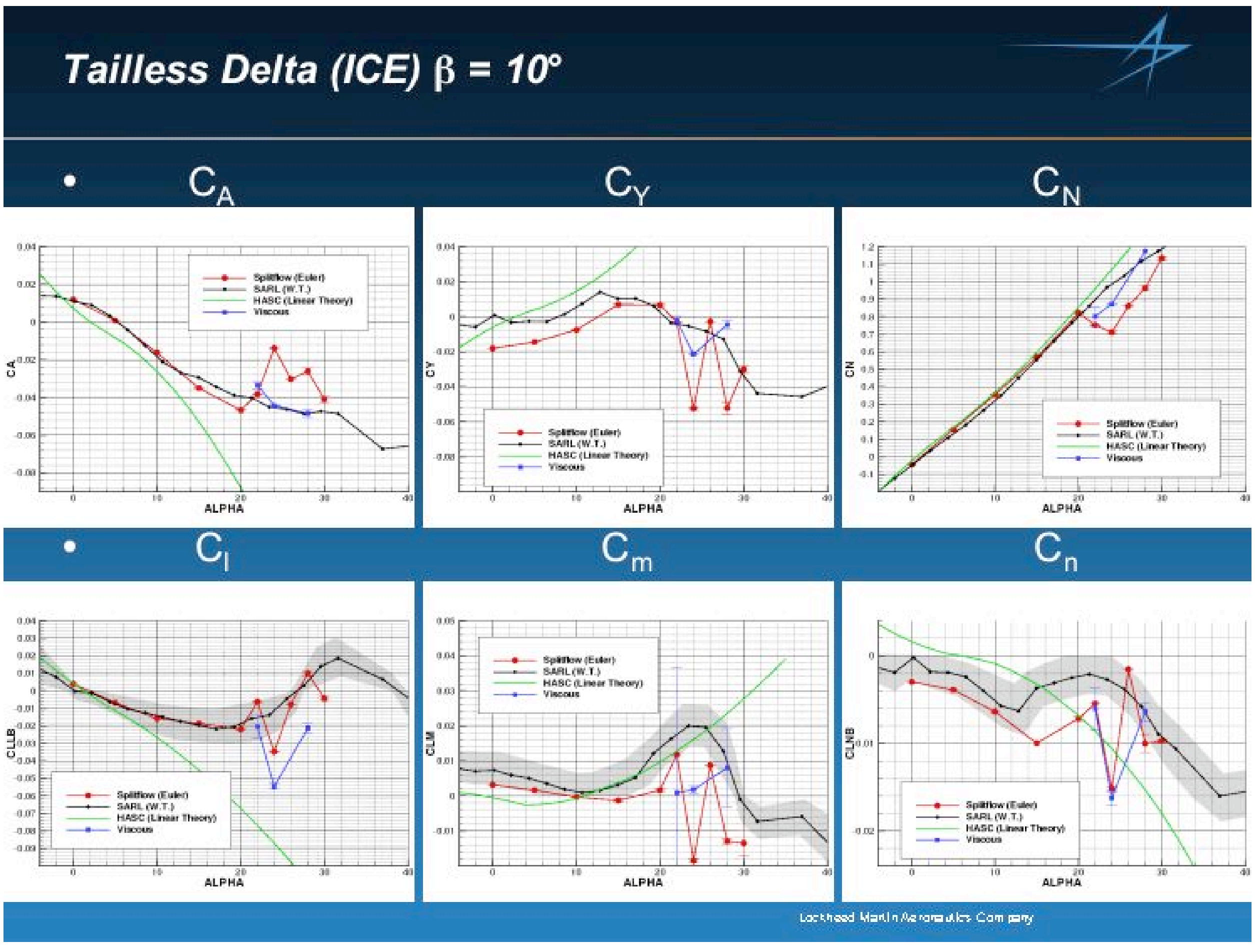
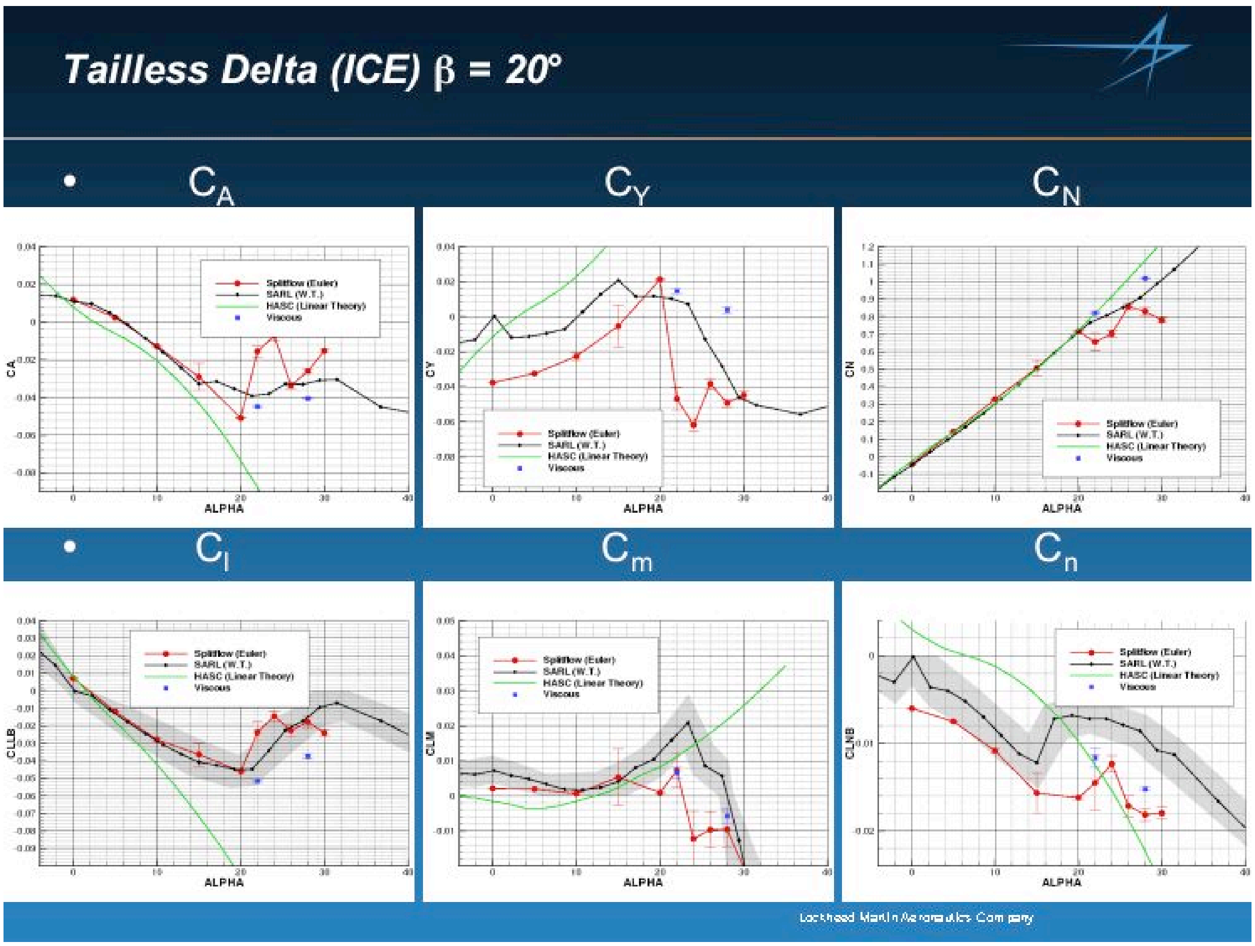
Originally, results were shown for each sweep listed above. Those results are included at the end for completeness but will not be presented here.



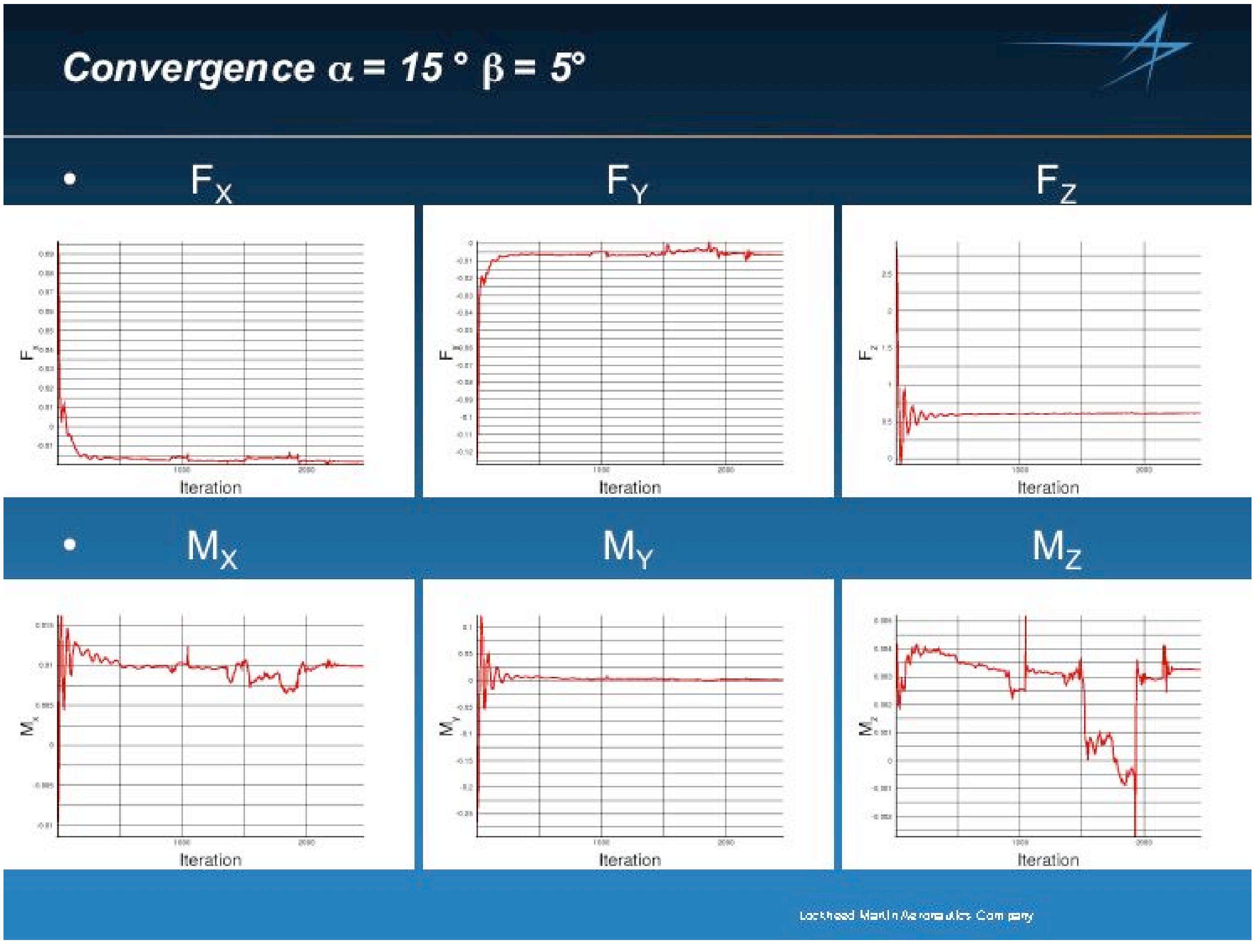
This condition is shown to highlight some of the success and some of the difficulty in this kind of CFD for S&C. Note that the results look "pretty good" until alpha>20. The error bars indicate how much change there was in the CFD results near the end of the run—note that some of these cases converged very well, just not to something that compares to the wind tunnel data.



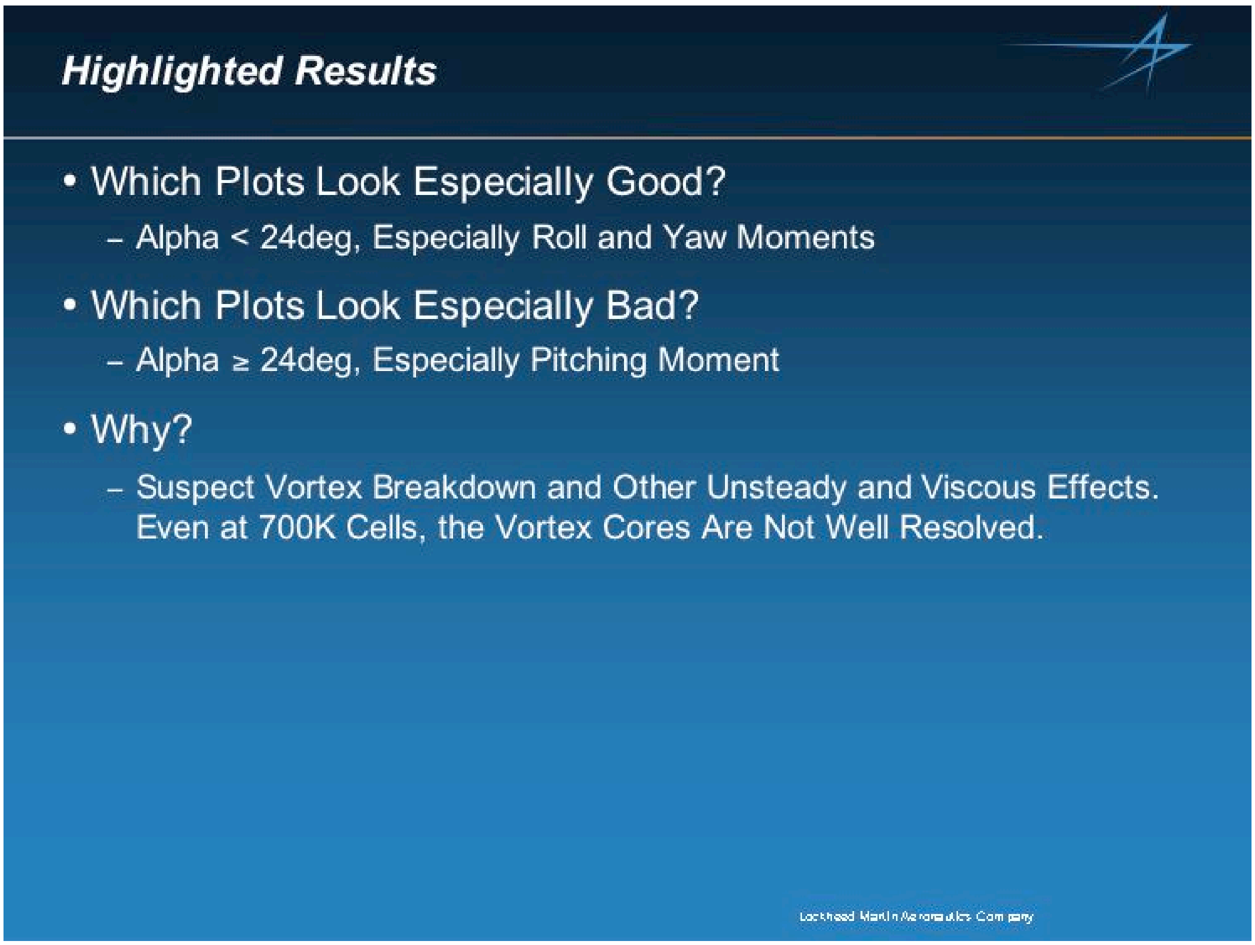
This group of results shows just how squirrelly some of the CFD analyses were. Note the pitching moment at alpha > 10 in particular, even though the general comparison to the wind tunnel data looks better than it did for the beta=10. Roll Pitch Yaw



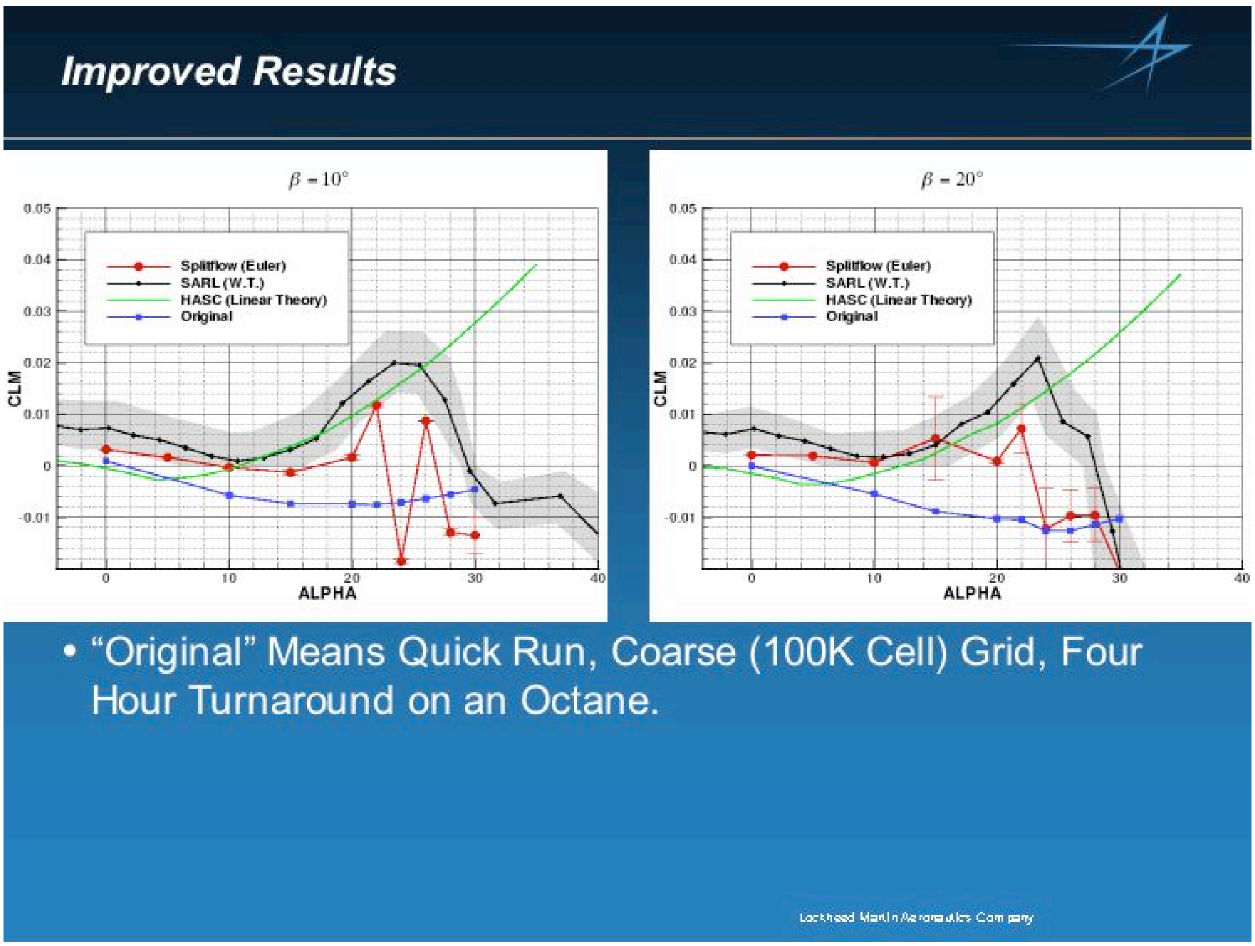
This is one example of the kind of convergence experienced on these CFD runs. Note the yawing moment, whose sign is questionable. The value itself is small, however.



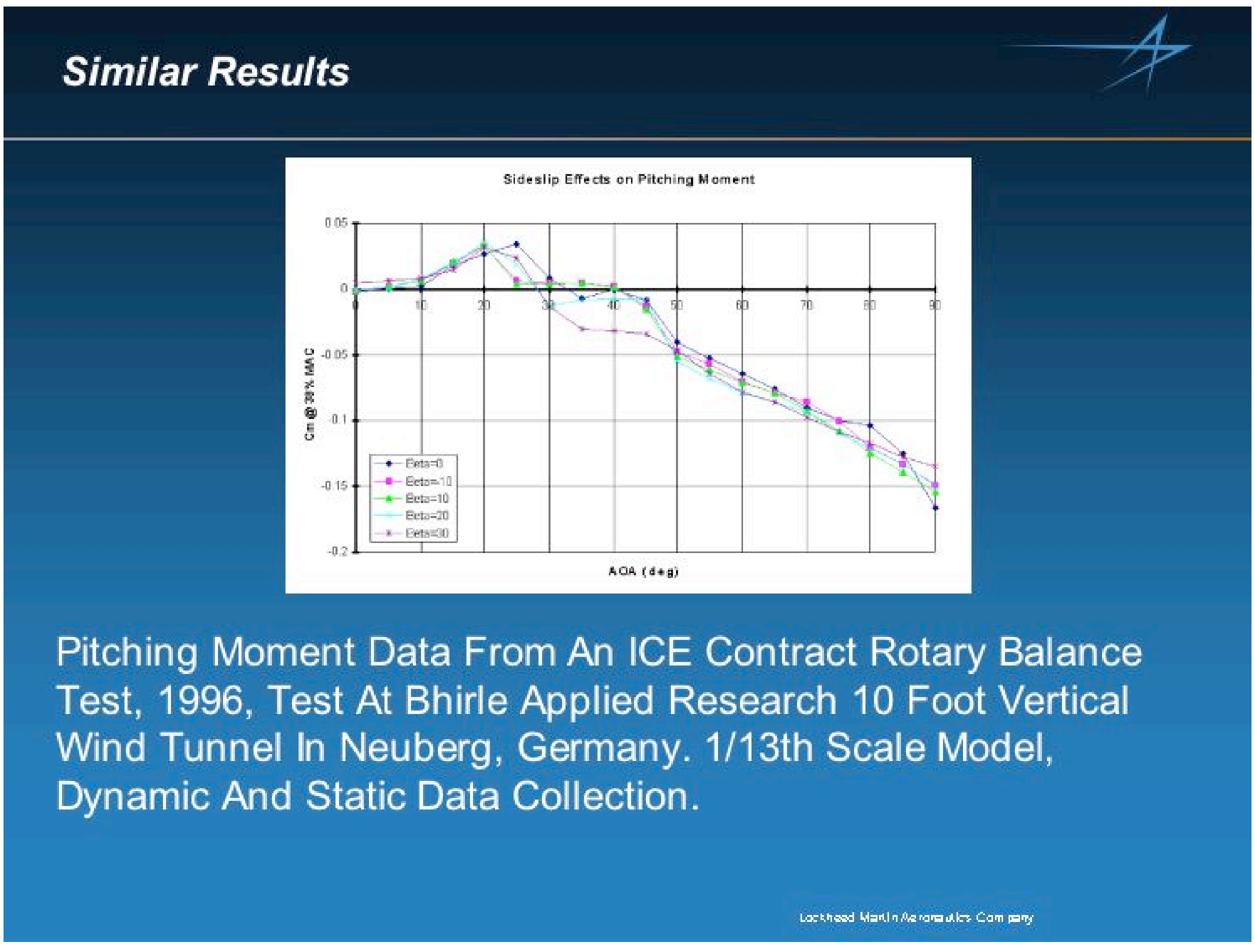
Some good results, some bad. At lower AOA, where 24 degrees isn't all that low, the results could be pretty useful. Above 24 degrees, with massive separation, vortex breakdown, and maybe other effects, the results were unpredictable.



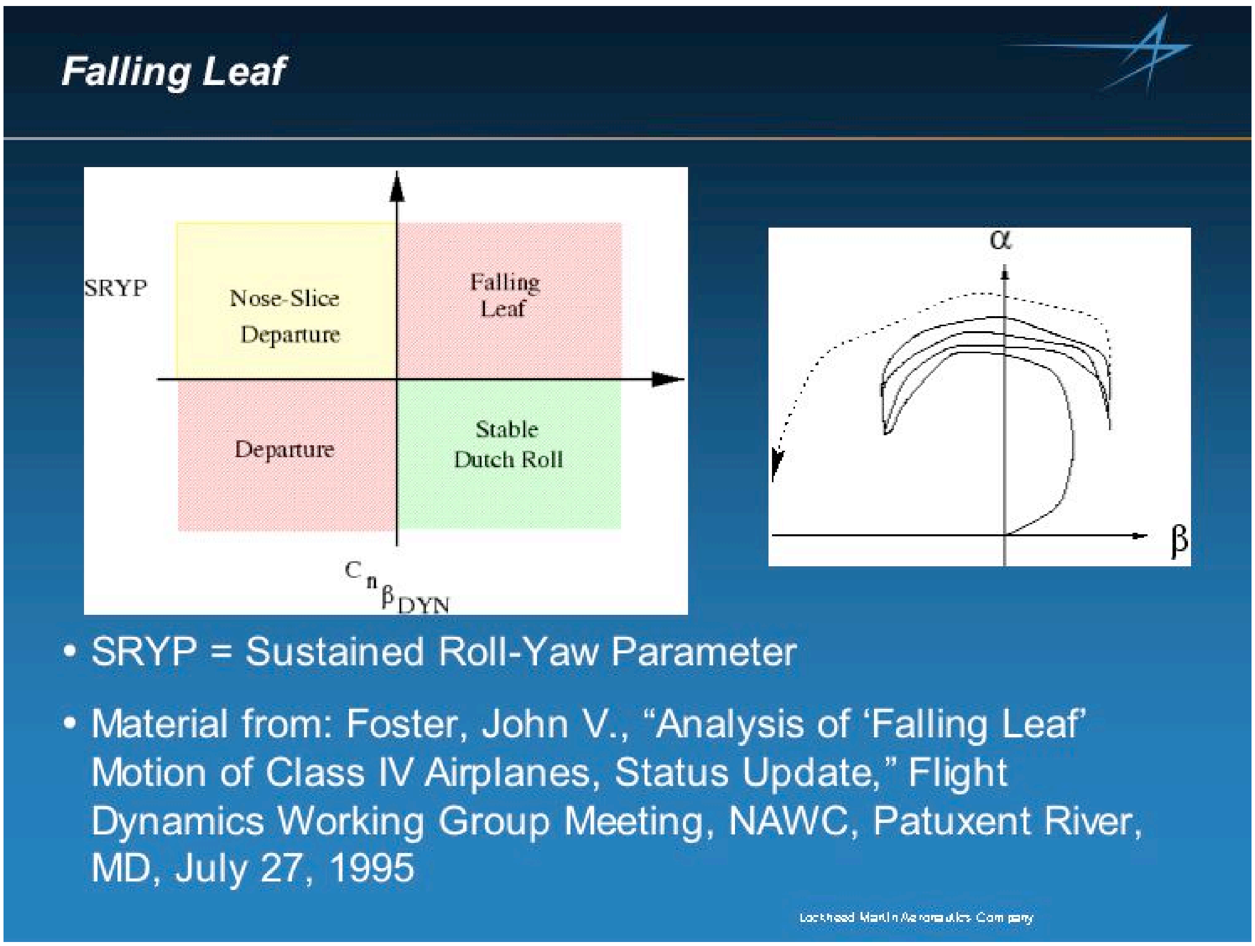
This shows some of the emphasis and difficulty in reproducing tunnel results. The error bars on the CFD values show how much the data was changing as the run "converged." Note that the for the left case, all of the runs converged quite well; at 24 degrees, it converged to something completely different from what was measured in the wind tunnel. At 20 degrees sideslip, beyond 14 degrees, the CFD really did not converge very well at all. One thing to keep in mind is that we do not know what the degree of variation of the wind tunnel data was.



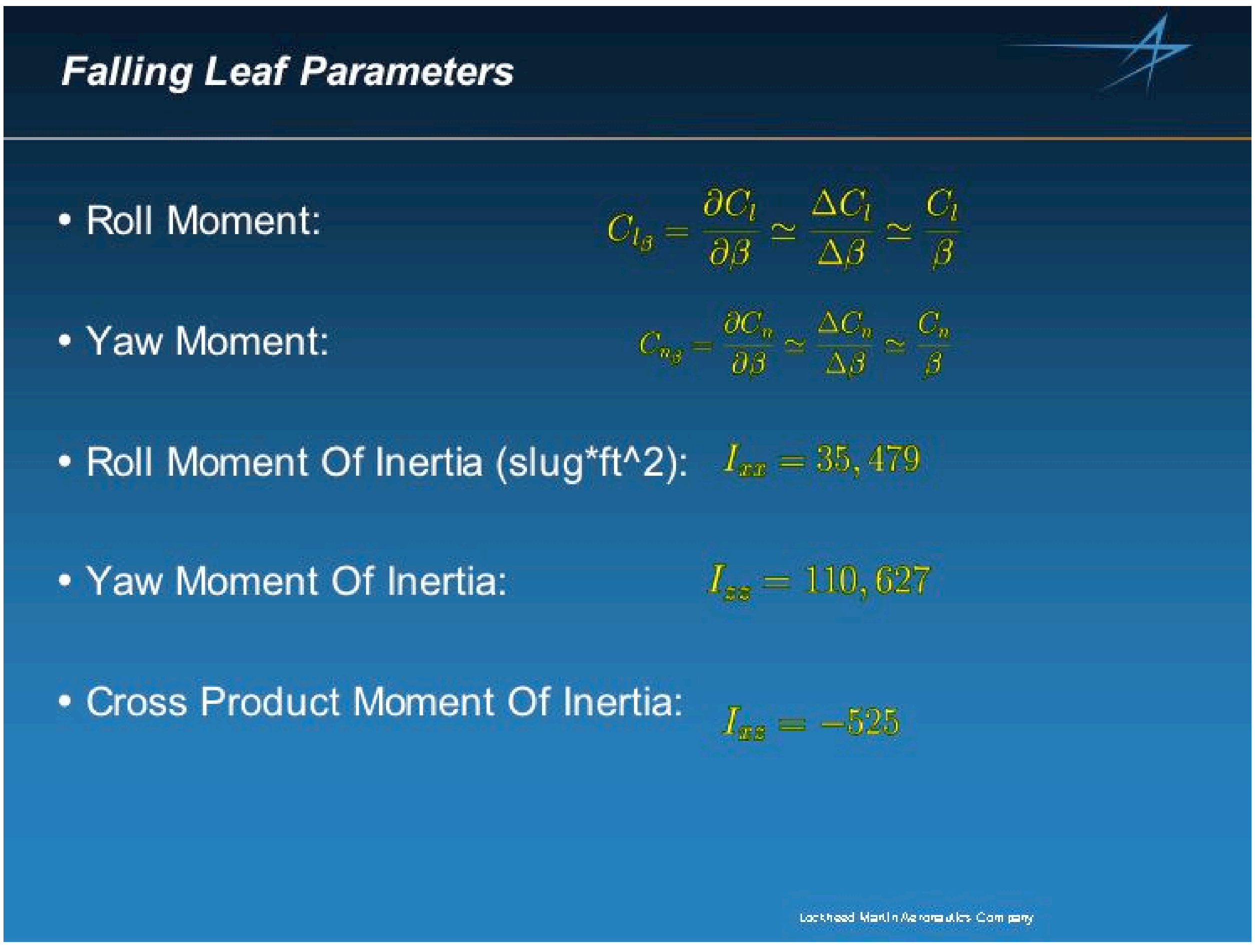
This test of the same ICE model shows that some of the wind tunnel data may not be as certain as it is credited. Note particularly that the 20 and 30 degree sideslip data lie between the 0 and the +/-10 degree sideslip curves, indicating that something happens to change the pitching moment, and then it comes back.



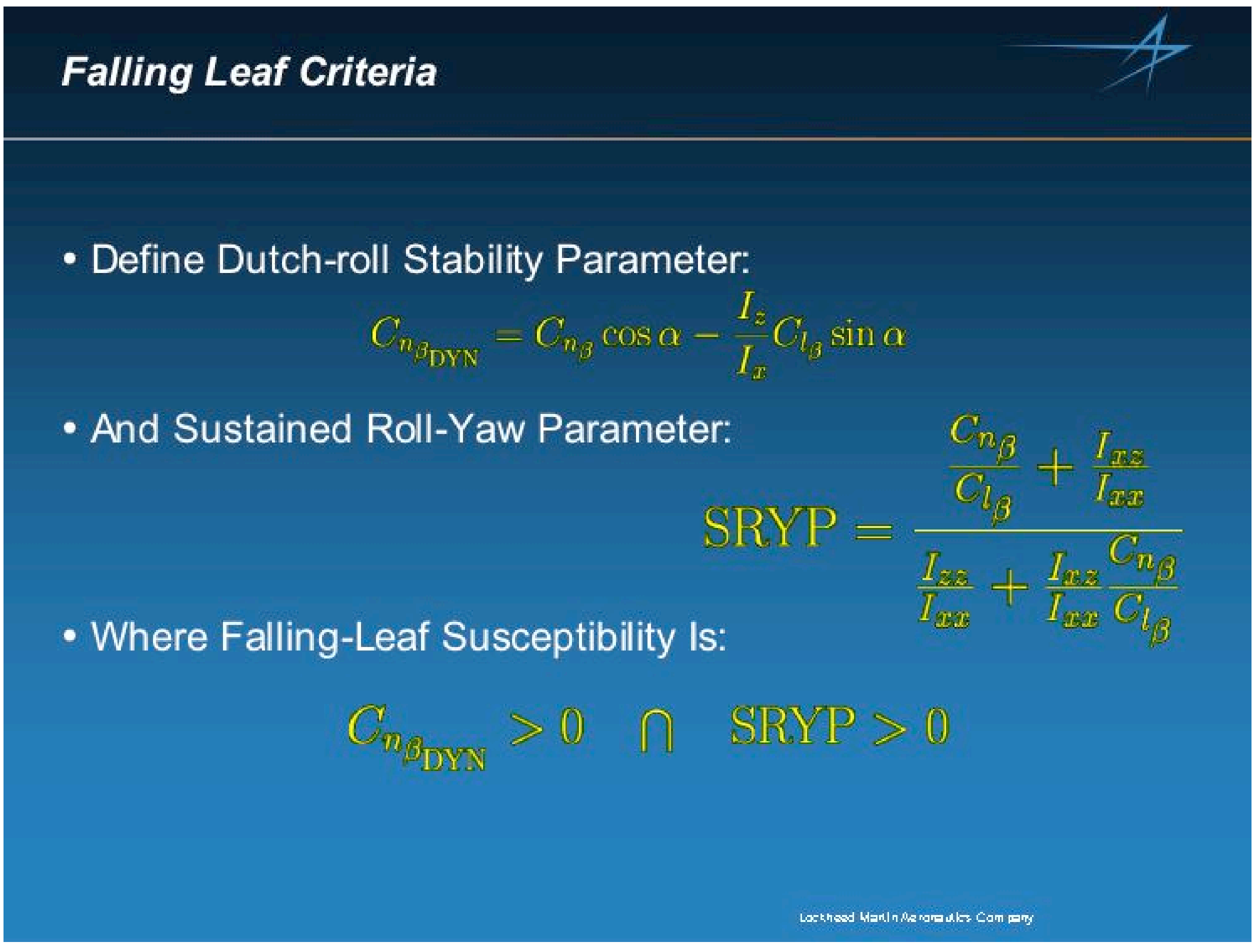
Falling Leaf is an extreme flight condition where the airplane rapidly transitions between high beta and low alpha, to high alpha and zero beta, on to high alpha and high negative beta, and then back. The Sustained Roll-Yaw Parameter measures the susceptibility to Falling Leaf, compared to simple departure or a stable Dutch roll.



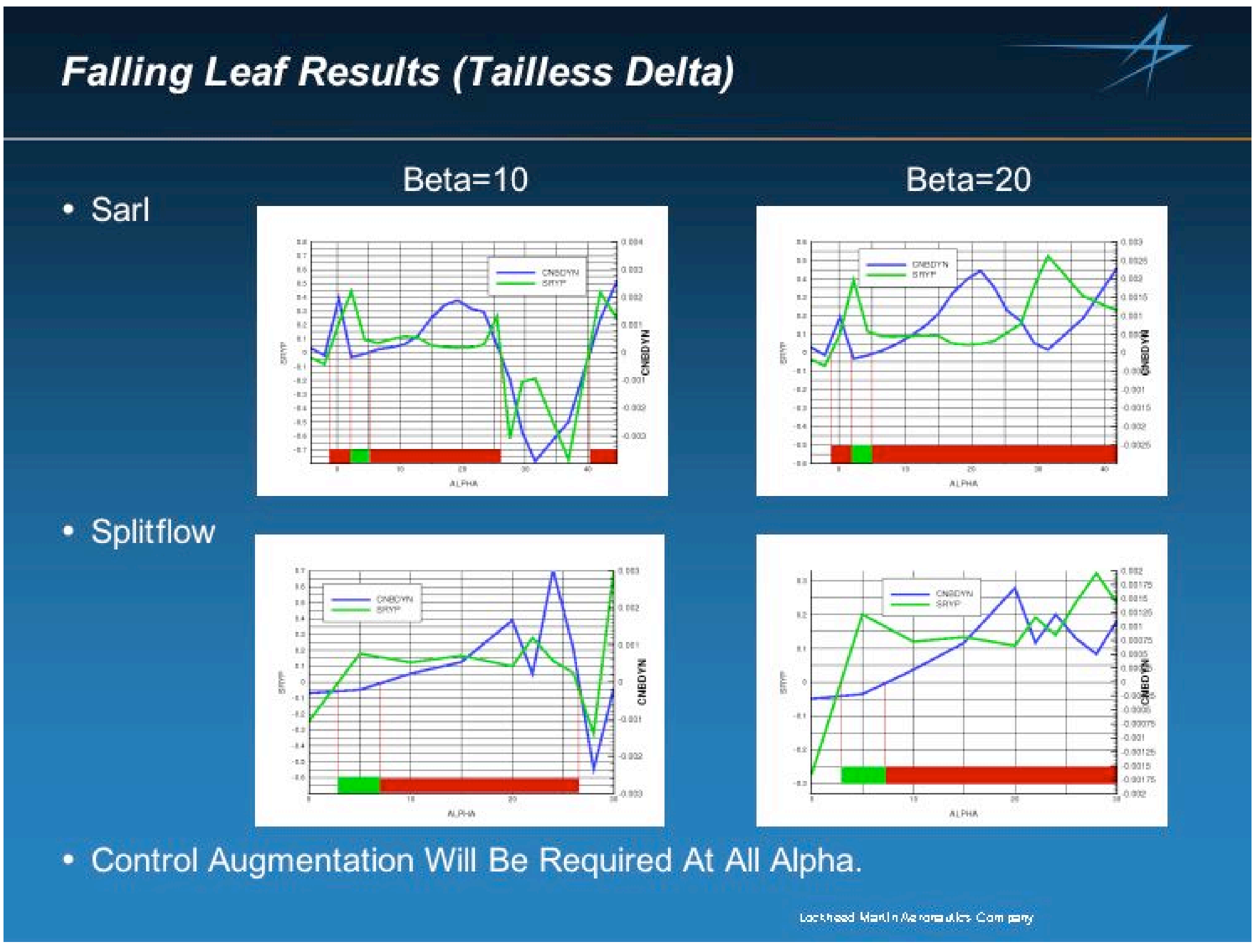
These are two definitions and the numeric values for the ICE configuration.



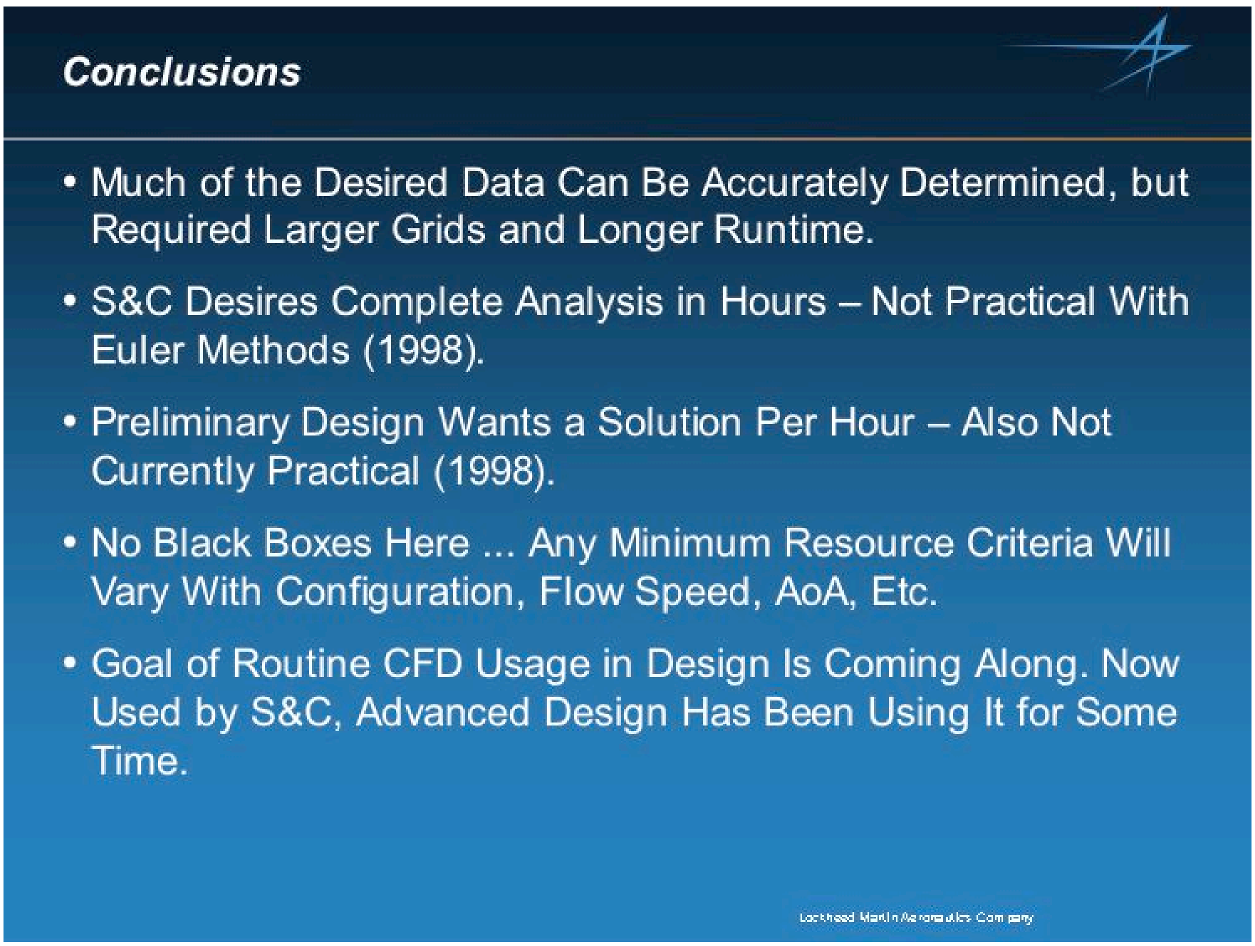
Then, defining those two parameters, we can check for susceptibility to Falling Leaf.



Now we can take both the wind tunnel dataset and the Splitflow dataset, compute the Dutch-roll parameter and the “syrup” parameter, plot them together, and determine the envelope susceptible to Falling Leaf. Here, the first important thing to note is that the Splitflow envelope prediction was pretty close to the wind tunnel; the second is that an active control system would be required for all angles of attack for this aircraft. Note that the x-scales are different between Splitflow and SARL data



These methods can produce useful results, and in fact these and similar methods are already in use in the LM Aero Advanced Design and S&C community. It may not be routine yet, and each needs large run matrices that are not yet supported by our CFD tools and computer resources. Another problem is that while this project set out to find a “black box” configuration, no such thing was determined, and in many cases each flight point CFD run required individual attention. Some of the performance applies to five years ago, too. Now, a lot of this analysis can be (and is) performed, opening up these requirements to apply to complete aircraft instead of the simpler configurations (ICE & MTVI) presented herein.



Acknowledgements

- Vortex Analysis: Dave Darmofal and Andrew Cary
- Advanced Design: Paul McClure
- S&C: Ken Dorsett
- Surface Preparation: Keith Jordan
- Splitflow Support: Neal Domel, Steve Karman, Brian Smith
- LMTAS Program Manager: Jim Robarge
- NASA Program Manager: Farhad Gaffari

The remainder of the presentation consists of support slides.

The MTVI model was run in an alpha sweep at zero sideslip and small (2 degrees) sideslip.

Configuration (MTVI)

MTVI, α-Sweep, Inviscid									
β	α								
0		12		20		30		40	
2	6	12	16	20	25	30	35	40	45

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The ICE model was run for an alpha sweep at several sideslip angles (0,5,10,20 degrees). A beta-sweep was also done at 20 degrees AOA.

Configuration (Tailless Delta) Inviscid

Tailless Delta, α-Sweep, Inviscid										
β	α									
0	0		10	15	20					30
5	0		10	15	20					30
10	0	5	10	15	20	22	24	26	28	30
20	0	5	10	15	20	22	24	26	28	30

Tailless Delta, β-Sweep, Inviscid								
α	β							
20	2.5	5.0	7.5	10.0	12.5	15.0	17.5	20.0

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A few viscous cases were also added to investigate the region near AOA=24 at sideslip, an area where the results compared poorly.

Configuration (Tailless Delta) Viscous

Tailless Delta, Viscous			
β	α		
10	22	24	28
20	22		28

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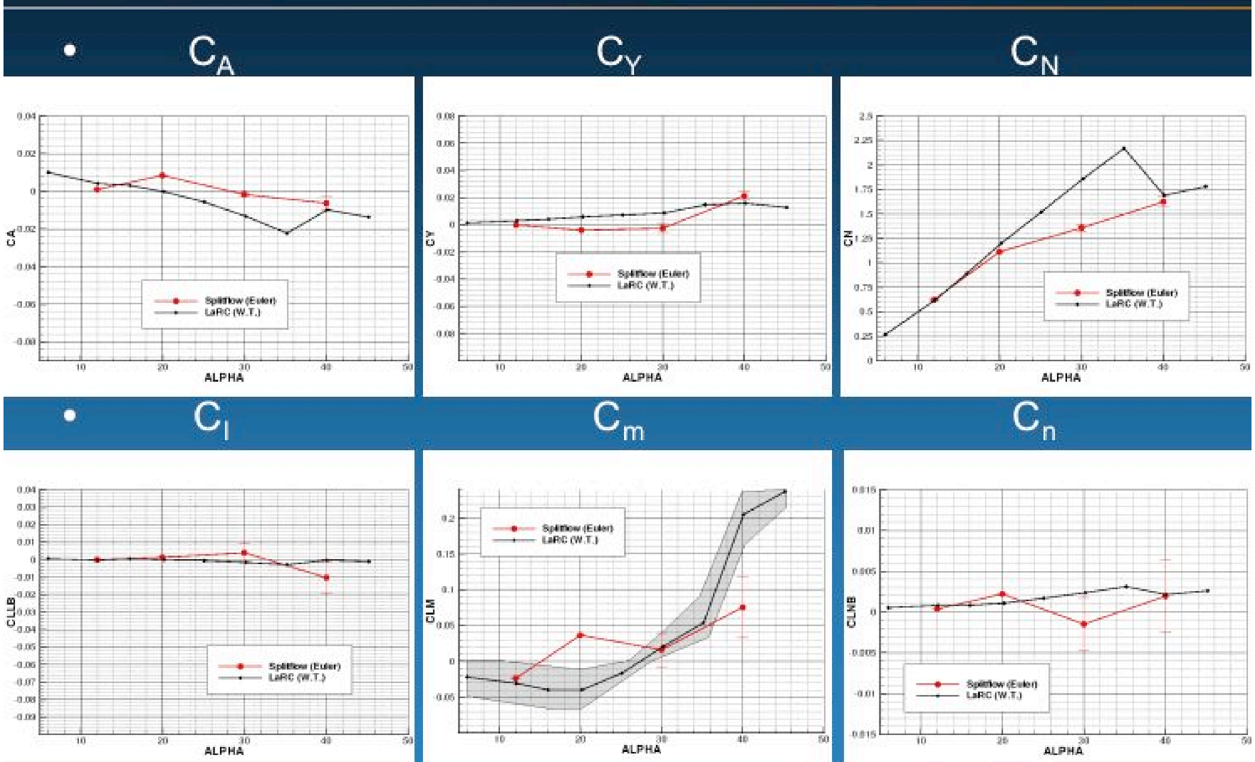
Results

- MTVI, α-Sweep
  - $\beta = 0$
  - $\beta = 2$
- Tailless Delta, α-Sweep
  - $\beta = 0$
  - $\beta = 5$
  - $\beta = 10$
  - $\beta = 20$
- Tailless Delta, β-Sweep

MTVI β = 0°



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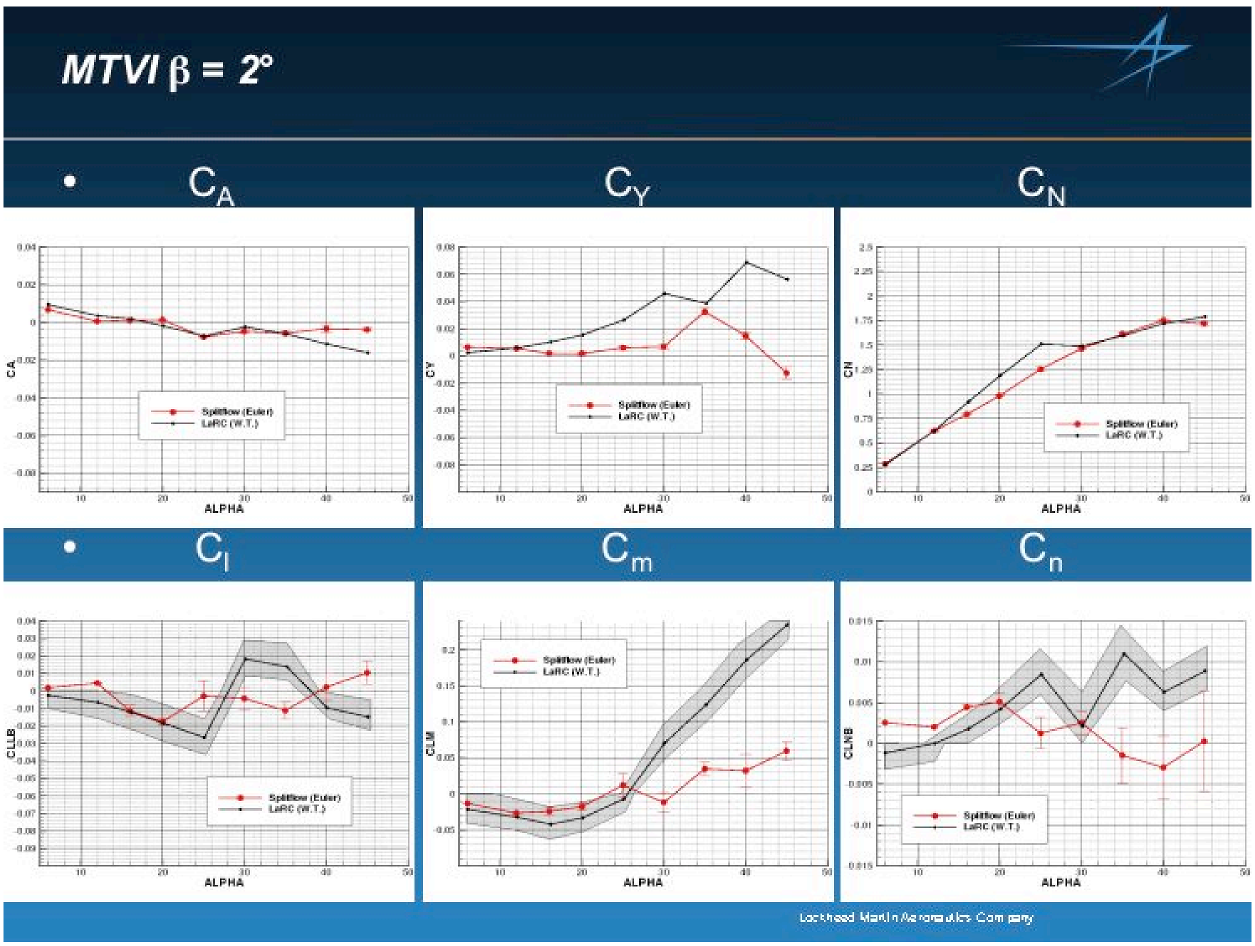
MTVI β = 2°
C_A
C_Y
C_N
C_l
C_m
C_n
CA
CY
CN
CLLB
CLM
CLNB
ALPHA
Splitflow (Euler)
LaRC (W.T.)
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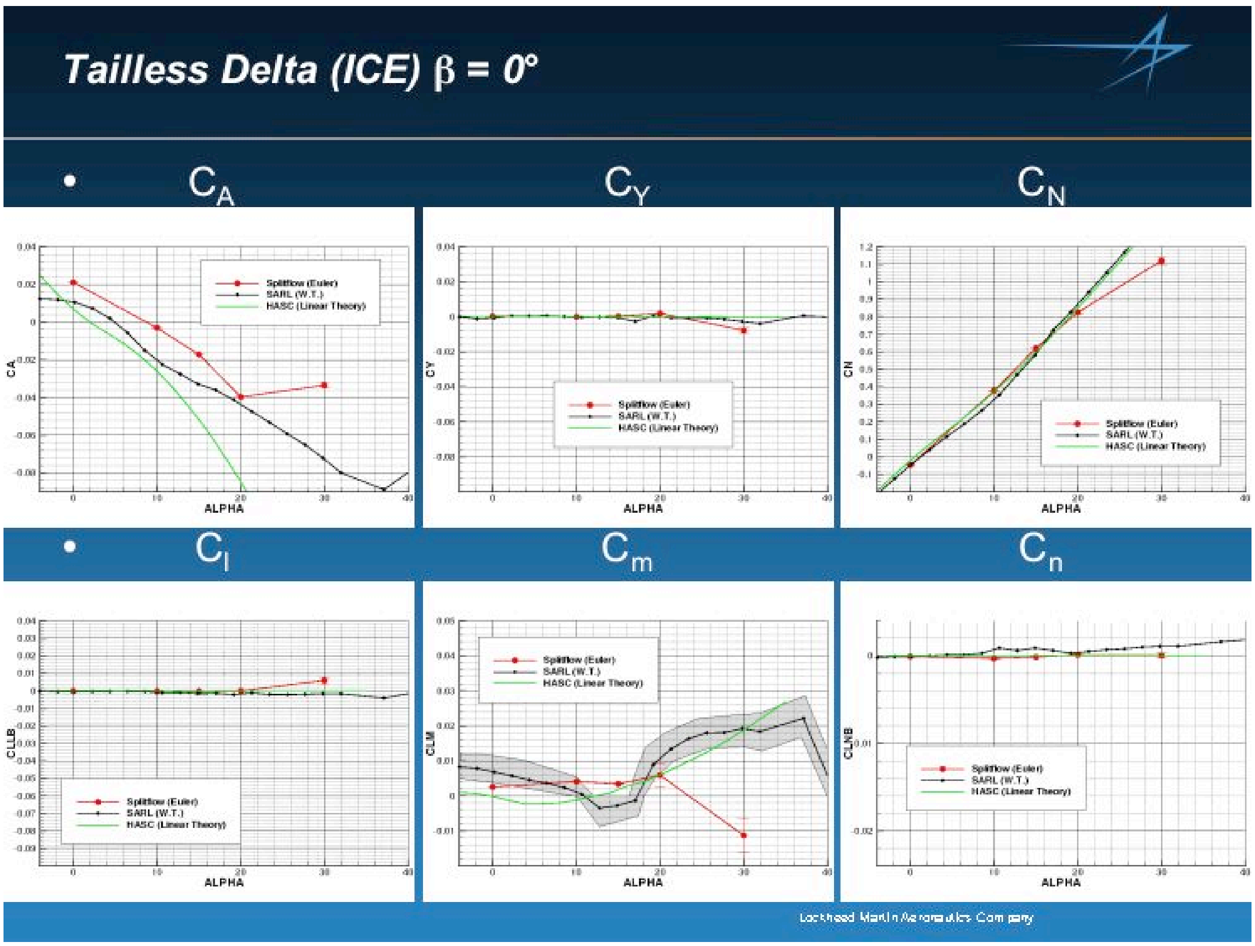
Tailless Delta (ICE) β = 0°
• C_A
C_Y
C_N
• C_l
C_m
C_n
Splitflow (Euler)
SARL (W.T.)
HASC (Linear Theory)
ALPHA
CA
CY
CN
CLLB
CLM
CLNB
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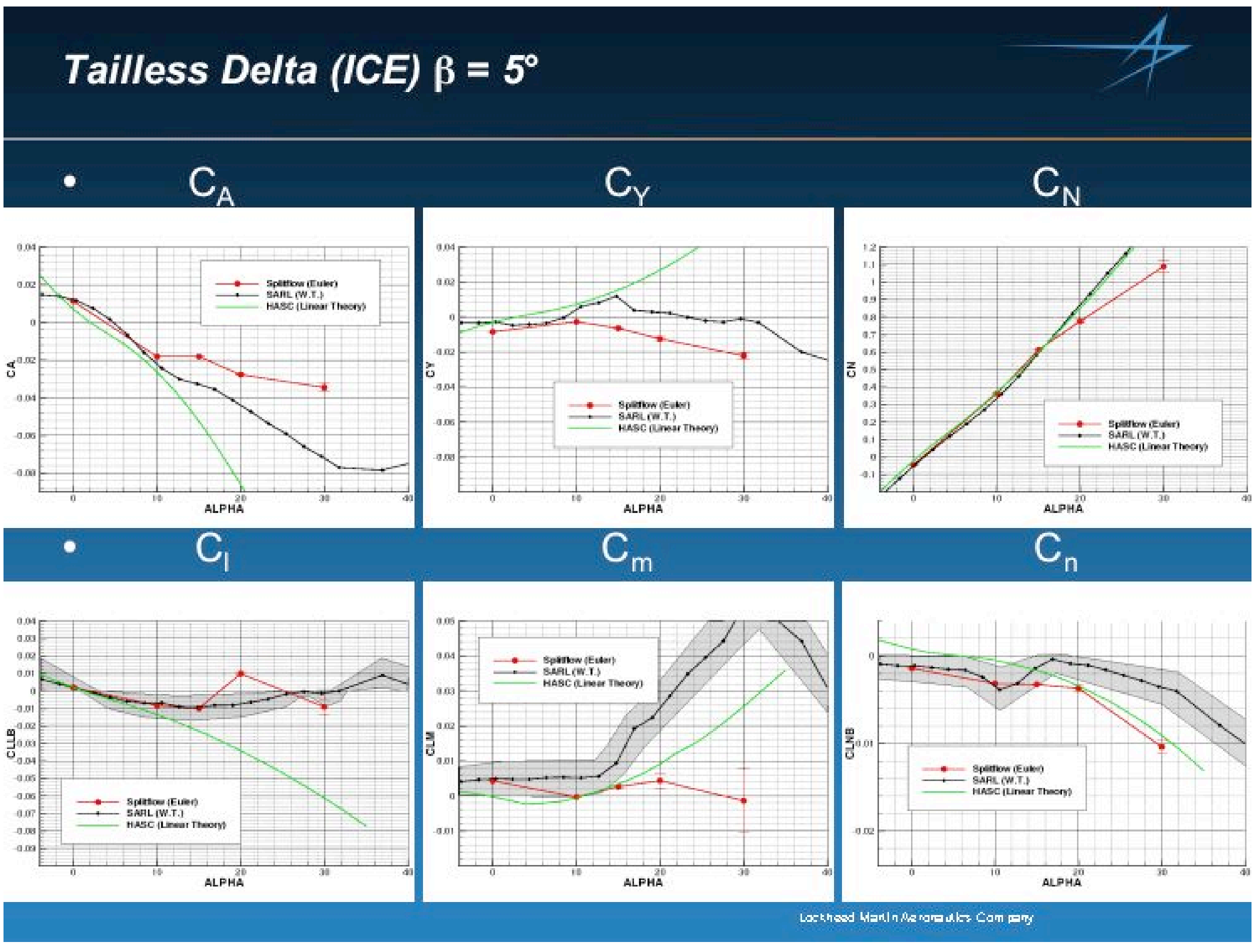
Tailless Delta (ICE) β = 5°
C_A
C_Y
C_N
C_l
C_m
C_n
Splitflow (Euler)
SARL (W.T.)
HASC (Linear Theory)
ALPHA
CA
CY
CN
CLLB
CLM
CLNB
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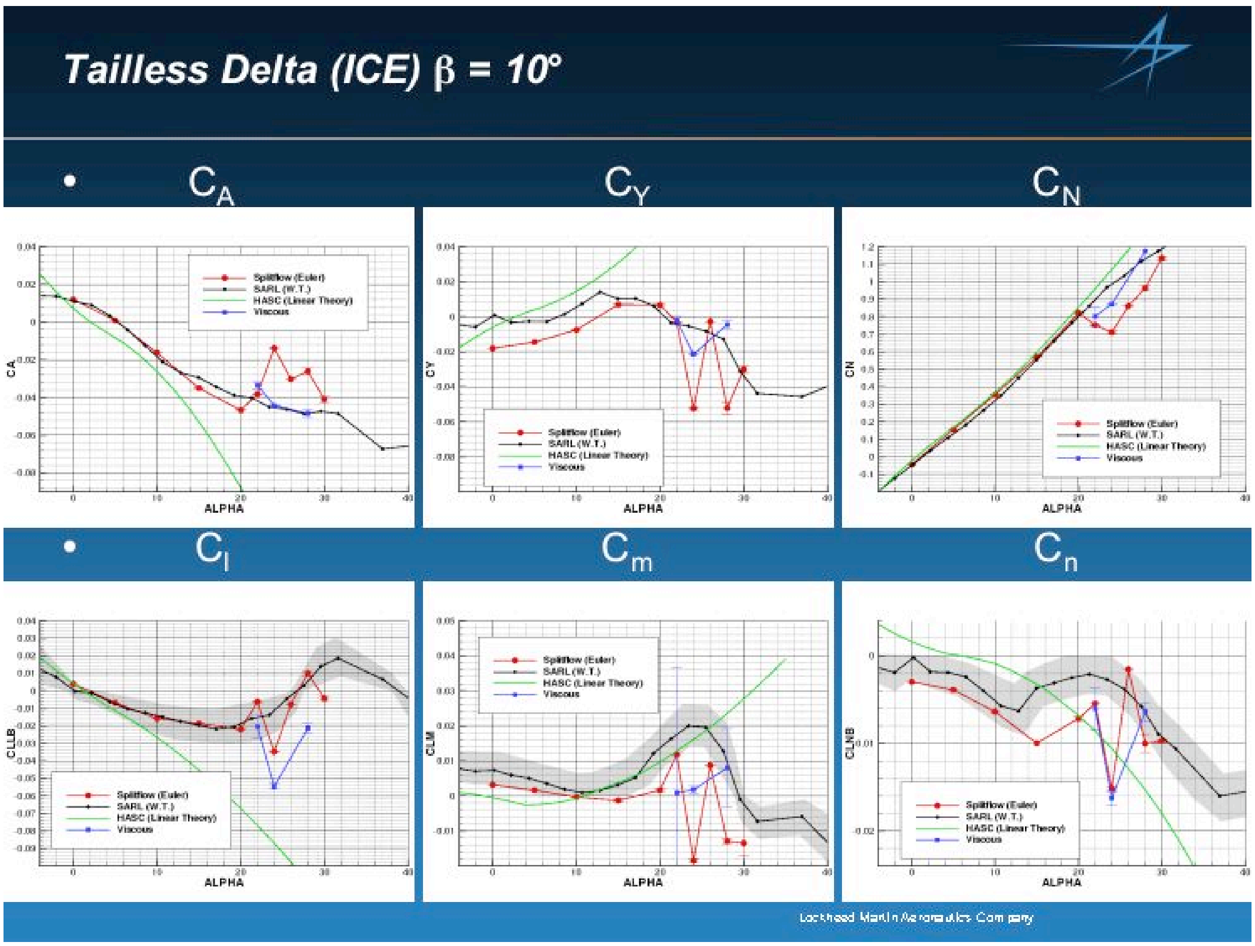
Tailless Delta (ICE) β = 10°
C_A
C_Y
C_N
C_l
C_m
C_n
Splitflow (Euler)
SARL (W.T.)
HASC (Linear Theory)
Viscous
CA
CY
CN
CLLB
CLM
CLNB
ALPHA
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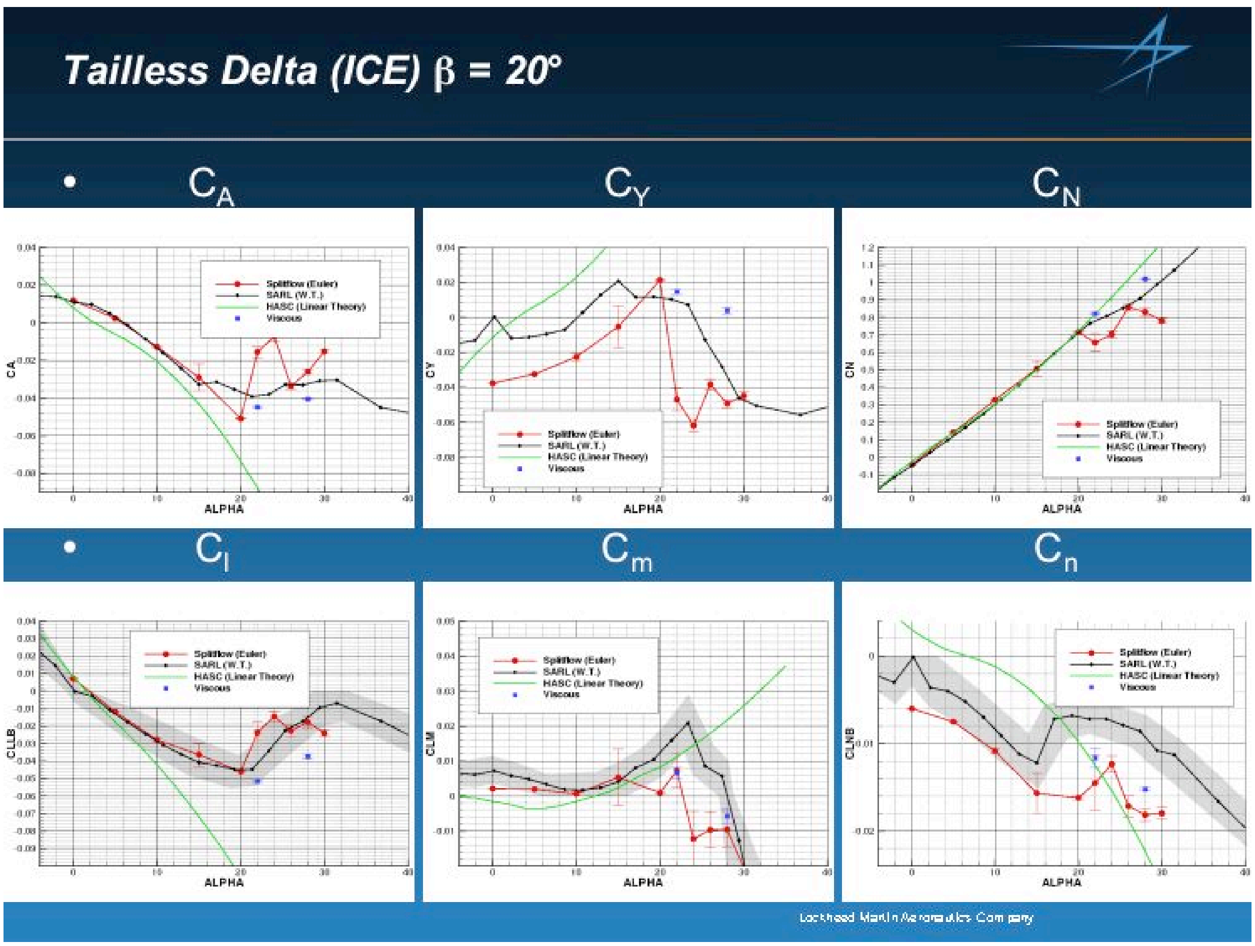
Tailless Delta (ICE) β = 20°
C_A
C_Y
C_N
C_l
C_m
C_n
Splitflow (Euler)
SARL (W.T.)
HASC (Linear Theory)
Viscous
ALPHA
CA
CY
CN
CLLB
CLM
CLNB
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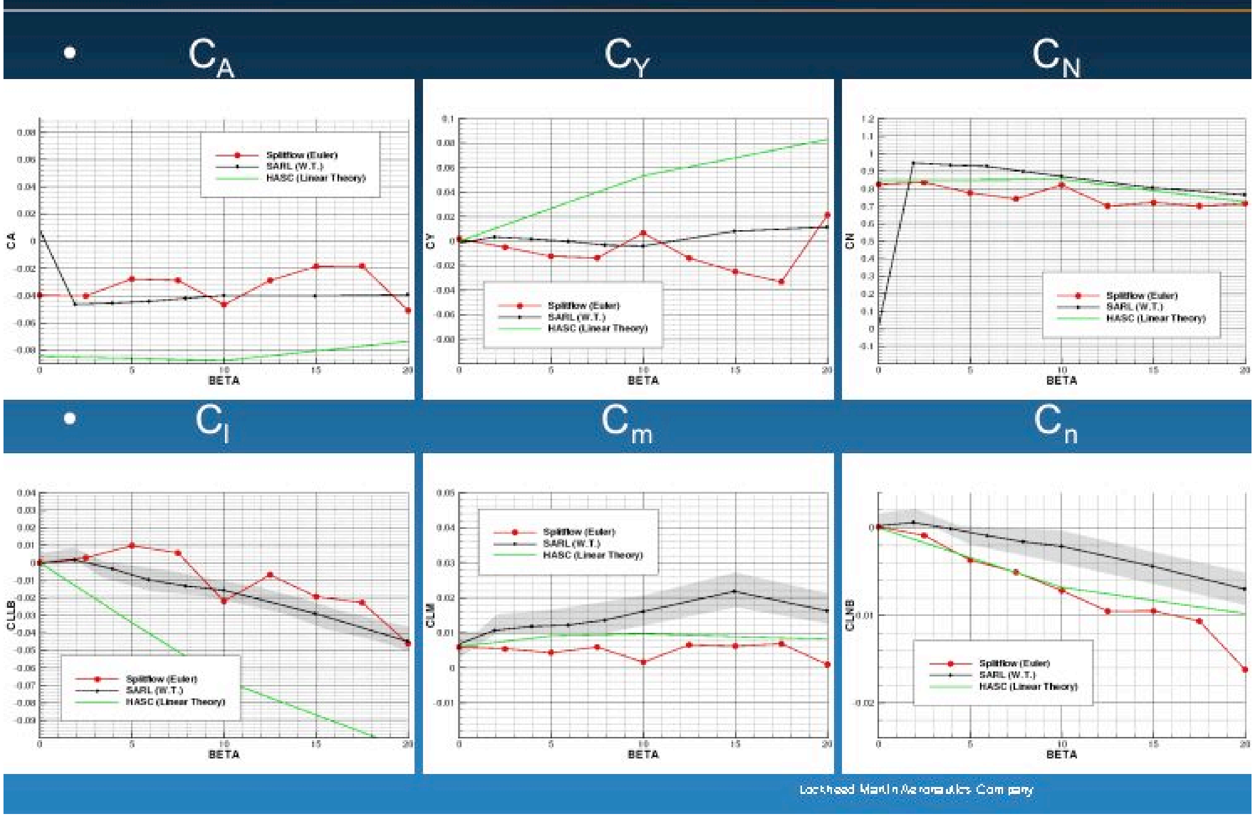
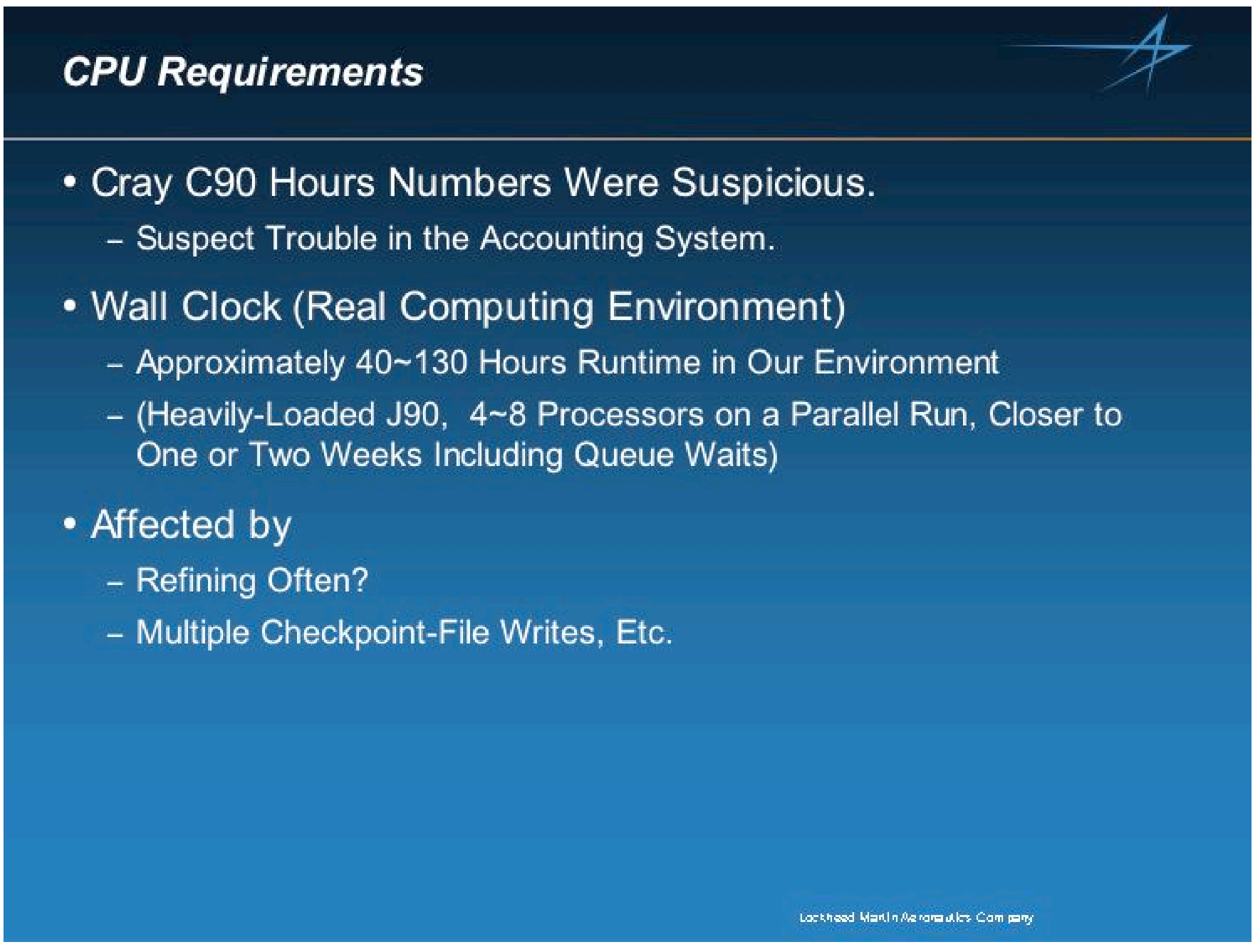
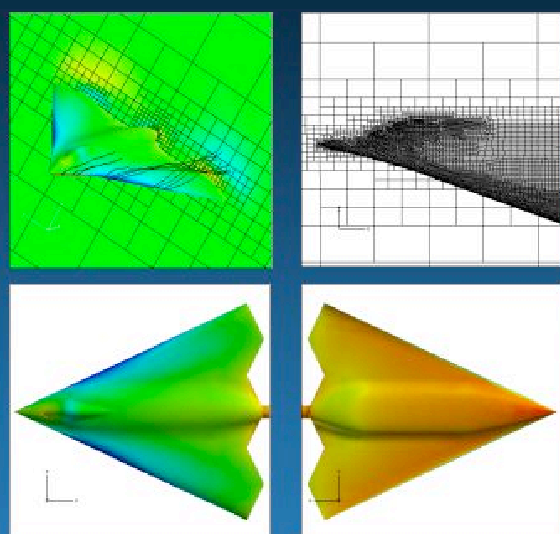
Tailless Delta β-sweep



Most of this is old news. Our J90 isn't even used to heat the room anymore. These cases would require about 4 hours on 16 CPU of our Pentium4 cluster, which is very inexpensive.



Future Efforts in Grid Generation



Research work on Splitflow is progressing to build grids that are more acceptable for viscous simulation.

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5 years ago, this is how this project concluded—we needed faster solutions and more of them. Minimum drag, of course, is now the subject of its own AIAA committee and annual meetings, and it doesn't seem that anyone has a good handle on it yet.